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STEEL
AND ITS PRACTICAL
APPLICATIONS

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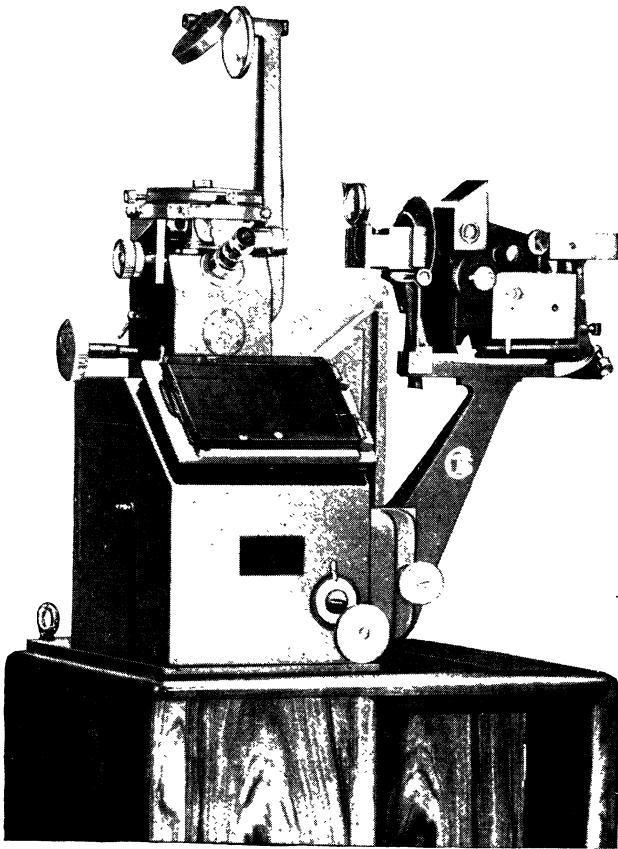
BLACKIE & SON (INDIA) LIMITED
Warwick House, Fort Street, Bombay

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THE PAPER AND BINDING OF THIS BOOK
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PLATE I



Vickers Projection Microscope

STEEL

AND ITS PRACTICAL APPLICATIONS

BY

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SECOND EDITION

BLACKIE & SON LIMITED
LONDON AND GLASGOW

First published 1932
Reprinted 1938, 1940, 1942
Second edition 1945
Reprinted 1946

Printed in Great Britain by Blackie & Son, Ltd., Glasgow

EXTRACT FROM PREFACE TO FIRST EDITION

The chemical, physical, and mechanical properties of iron are capable of variation over a remarkably wide range. Ferrous alloys, the vast majority of which are steels, are manufactured to specifications which have nothing in common with each other. For example, most steels are only too susceptible to atmospheric corrosion, and to other forms of chemical attack, while modern stainless steels are produced which are unchanged by the atmosphere, and are impervious to the action of many acids. Again, permanent magnets are manufactured from cobalt or tungsten steels, while iron or dead soft steel provides a material which loses its magnetism as soon as the magnetizing force is removed. Yet again, the tenacity of pure iron is about 17 tons per square inch, while steel wire containing 98 per cent of iron may have a tensile strength of more than 180 tons per square inch. Steel may be as ductile almost as copper, or as brittle as glass. Thus the varieties and grades of iron are almost innumerable. Truly, we live in *The Iron Age*. It is to this wonderful adaptability of iron to our requirements that we owe, in a very large measure, the great advances in engineering science which have been and still are being made.

The purpose of this book is to describe for the engineer, as simply as possible, the actual nature of the ferrous materials at his disposal, the processes which they must undergo to ensure their fitness for his particular requirements, and the means by which he may detect and trace to their source defects in material or workmanship. Metal-working, as an art, is as old as history: as a science it is very young and it still suffers from growing pains.¹ The metal doctors (to continue the metaphor) are unanimous neither in diagnosis nor in treatment. Many important matters such as the constitution of the iron-carbon equilibrium diagram, the cause of temper brittleness in steels, and the mechanism of corrosion, are still

¹ The microscope was first adapted to the study of metals by Sorby in 1887.

the subject of controversy, and unanimity may not be reached for some time. Such matters of argument, however, may be left to the experts and are here, as far as is practicable, ignored. The limitations of space demanded much pruning and considerable compression, but it is hoped and believed that no essential matters have been crowded out. The omission of detailed descriptions of the metallurgical microscope and of thermo-couples is deliberate. Such descriptions are supplied at length in makers' or merchants' catalogues.

PREFACE TO SECOND EDITION

In recent years the principal advances in ferrous metallurgy have been in the fields of mass-effects in heat-treatment, creep, and weldability. Accordingly, for this edition the chapter on heat-treatment has been re-written and new material on creep and weldability added. Numerous alterations have been made in other chapters to bring them up to date. For example, the necessities of war have resulted in drastic changes in the composition of alloy steels. The properties of the more important of the new steels (known as the En. steels) are described, with special acknowledgment to the Technical Advisory Committee of the Iron and Steel Control, which has been responsible for the introduction of these steels and whose invaluable summary of their properties and applications is published by the British Standards Institution (B.S. 971).

The authors gratefully acknowledge their indebtedness to their Directors for permission to make use of information obtained in the course of their duties, and to their colleague, Mr. A. Fisher, who has prepared most of the illustrations; also to Mr. S. L. Robertson of The Clyde Alloy Steel Coy. Ltd., who has read the proofs and made some valuable suggestions.

W. B.

A. J. K. H.

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CHAPTER I

The Testing of Iron and Steel

A complete description of all the tests carried out on ferrous materials is beyond the scope of this book, but a brief survey of the tests common to most material specifications is necessary.

Tensile Test

✓ This test is the most important and most useful means of examining the quality of materials. The machine in general use is of the single-lever vertical type, and is illustrated diagrammatically in fig. 1. The lever floats between stopper

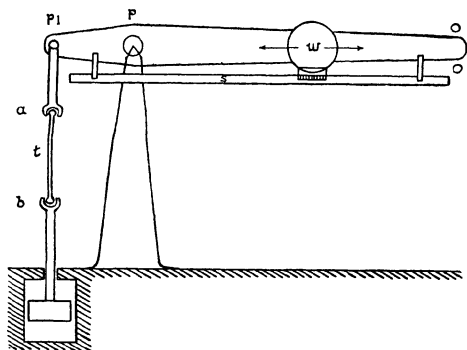
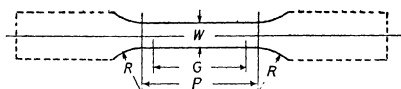


Fig. 1.—Tensile Testing Machine

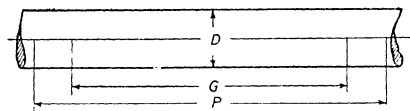
ends, on the knife edge p . A scale s on the lever is marked in tons and tenths of a ton, the dimensions of the scale depending on the distance between the knife edges p and p_1 , and the weight of the poise w which rests on and is free to move along the lever. The poise weight is usually called the Jockey. The vernier scale on the jockey is so adjusted that when the reading is 0 tons, the lever floats freely. The test piece t is fixed at a and b , the upper shackle being suspended from the

STEEL

TEST PIECE A



Nominal thickness of test piece		(i)	(ii)	(iii)	(iv)
		in.	Up to but not including $\frac{3}{8}$ in. in.	in.	$\frac{3}{8}$ in. and over in.
Width	W	$\frac{1}{2}$	1	$1\frac{1}{2}$ (max.)	$1\frac{1}{2}$ (max.)
Gauge length ..	G	2	4	8	8
Parallel length (minimum) ..	P	$2\frac{1}{2}$	$4\frac{1}{2}$	9	9
Radius at shoulder (minimum) ..	R	1	1	1	1
Approximate total length		8	12	18	18

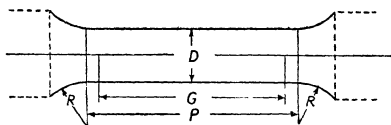
TEST PIECES B AND B₁

Test Piece B.

Test Piece B₁.

Gauge length G	=	8D	4D
Length between Grips P	=	not less than 9D	not less than 4.5D

TEST PIECE C AND SUB-STANDARD TEST PIECES



	Test Piece C.	Sub-Standard Test Pieces.
Cross-sectional area	·25 sq. in.	$D^2 \frac{\pi}{4}$
Gauge length, G	2"	$4 \sqrt{\text{area}}$
Parallel length, P	$2\frac{1}{4}$ "	$\frac{9}{8}G$
Radius at shoulder	$\frac{1}{2}$ " min.	0.88D min.

Fig. 2.—British Standard Test Pieces

knife edge pr . The load is applied hydraulically or electrically, the downward pull being balanced by moving the jockey along the lever. The breaking load is the load at which the test piece is unable to maintain the lever floating, the downward pull being absorbed by the stretching of the test piece until fracture takes place.

Commercial tensile testing machines are regularly examined and calibrated and are accurate to a very high degree.

Preparation of Test Pieces

The size and shape of the test piece depend upon the material from which the test is taken, the gauge length to be employed in measuring the elongation, and the grips used in the testing machine. For plates, flats, and sections, the British Standards Institution has standardized test piece A (fig. 2). It will be observed that the parallel portion of the test piece is greater than the gauge length. This permits free elongation over the

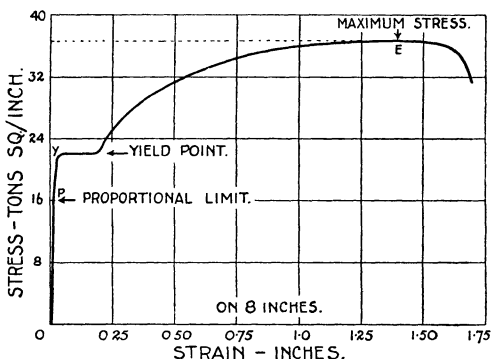


Fig. 3.—Stress-strain Diagram

whole of the gauge length. Within certain limits, the elongation increases with an increase in cross-sectional area, and to obtain concordant results limitations are set on the width according to the thickness of the plate or section. While the dimensions permitted are more or less arbitrary, they are sufficiently near to the true relation between sectional area and elongation for practical purposes.

Round test pieces are more easily standardized, and this

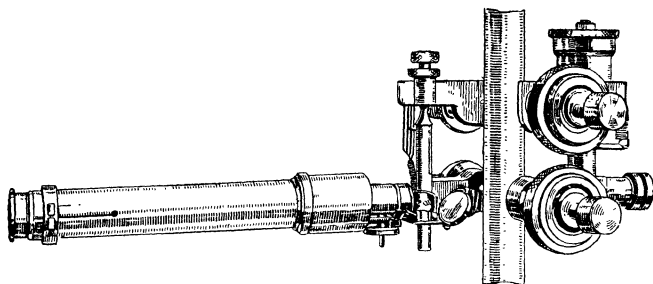


Fig. 4.—Ewing Extensometer

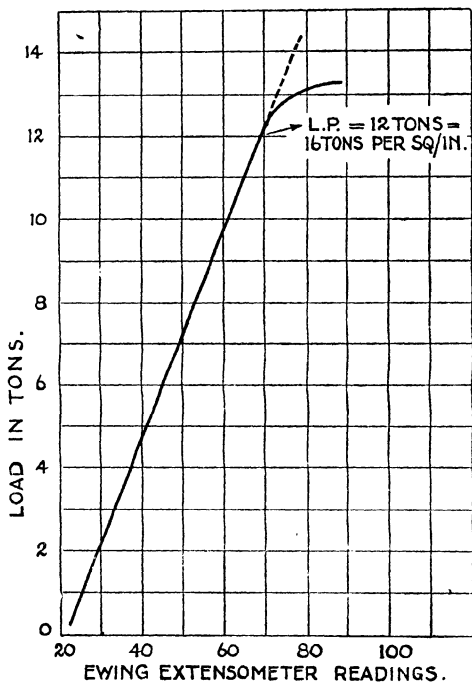


Fig. 5

has been done by the B.S.I., whose standard round test pieces are also shown in fig. 2. Test piece B is used chiefly for un-machined bars up to 1 in. diameter, test piece B₁ for un-machined or machined bars over 1 in. diameter. Test piece B corresponds closely to test piece A in the elongation obtained, while test piece C, and the subsidiary standard round

TABLE I.—RESULT OF TENSILE TEST

TEST	DIMENSIONS			YIELD POINT		MAX. STRESS		ELON.
N ^o	THICK	WIDE	AREA	TONS	TONS	TONS	TONS	%
468D	INCH	INCH	SQ IN	ON PIECE	PER SQ IN	ON PIECE	PER SQ IN	8 INS
	.50	1.50	.750	16.5	22.0	25.4	34.8	21.0
	.34	1.21	.411	AT FRACTURE = RED OF AREA, 45.2%				
EWING EXTENSOMETER READINGS.								
LOAD IN TONS		READING		LOAD IN TONS		READING		
1.0		25.0		9.0		57.0		
2.0		29.0		10.0		61.0		
3.0		33.0		10.5		63.0		
4.0		37.0		11.0		65.0		
5.0		41.0		11.5		67.0		
6.0		45.0		12.0		69.0		
7.0		49.0		12.5		71.5		
8.0		53.0		13.0		77.0		
EXTENSION PER TON WITHIN L P. = 4 X .0002 INCH.								
EXTENSION PER TON PER SQ IN. PER IN. LENGTH =								
4 X .0002 X .750 ÷ 8								
YOUNG'S MODULUS = $\frac{8}{4 \times .0002 \times .750}$								
= 13300 TONS PER SQ. INCH.								

test-pieces, are strictly comparable. Test piece B₁ is in practice comparable to test piece C, test pieces with a diameter greater than 1.5 in. being rarely employed. As is to be expected, a greater elongation is obtained with test piece B₁ than with test piece B (see fig. 6), and provision for this is made in specifications where either of these test pieces is permitted. The ends of round test pieces are shaped to suit the shackles of the testing machine.

The behaviour of steel under a tensile stress is conveniently examined by plotting a curve showing the relation between the stress and the strain thereby induced. The load extension curve has the form shown in fig. 3. From zero stress to P, the strain is proportional to the stress, and the slope of the straight line OP is a measure of Young's Modulus. Beyond this value the strain increases at a greater rate and at Y (the yield point) there is a sudden increase in strain without increase in stress. The maximum stress (E) usually produces considerable elongation before the test piece breaks. In commercial testing the limit of proportionality is determined by means of an extensometer, which is capable of measuring strains of the order of .0001 in. The gauge length used is either 2 in. or 8 in., and the extensometer commonly employed is that designed by Professor Ewing (see fig. 4). The Yield Point is determined by the drop of the testing machine lever or is "that point at which a distinctly visible increase occurs in the distance between the gauge points on the test piece as measured by dividers".¹ An example of a complete record of a tensile test is given by fig. 5 and Table I.

Information obtained from the Tensile Test

Young's Modulus

This may be defined as that stress which would produce a strain of 100 per cent, assuming perfect elasticity up to that point. Its value for steel is about 13,000 tons per square inch, and is not appreciably affected by mechanical or thermal treatment.

Limit of Proportionality (L.P.)

As its name indicates, the L.P. is that stress above which the strain ceases to be proportional to the stress. It is also called the Elastic Limit, but the use of this expression is to be deprecated, as there is no essential agreement between the two properties. Values for the L.P. are included in a few specifications only. Considerable differences of opinion exist as to the advantages of including this test, but whatever its merits or demerits may be from an engineering point of view, it is certain that the specification of a high L.P. ensures that

¹ B.S.I. definition of yield point.

the material will be most carefully heat-treated, for otherwise it will fail to meet requirements. Test pieces which have to undergo this test must of necessity be straight when cut from the material, as cold work reduces the L.P. considerably. The value of the L.P. varies from about one-quarter to as high as three-quarters of the tensile strength, depending upon the composition and heat treatment of the steel.

The Yield Point (Y.P.)

The yield point strangely enough is also frequently miscalled the elastic limit, and here with no justification whatever, for it is always higher, and frequently considerably higher, than the elastic limit. In normal steels it is seldom less than 50 per cent and in heat-treated steels may be as high as 95 per cent of the tensile strength.

Proof Stress (P.S.)

This has been suggested as a substitute for both the limit of proportionality and the yield point. It has been asserted that the value obtained for the limit of proportionality depends upon the sensitiveness of the extensometer employed, and also that the time required to carry out a test is too long for practical purposes. Objection to the yield point is also based on the fact that in certain steels there is no well-defined "sudden extension" and that no real property is measured by the yield point.

The substitution of a proof stress, it is claimed, would remove the above objections and would provide a test which may be carried out quickly and accurately.

The test consists of applying and removing a specified load (the proof stress) and measuring, with a suitable extensometer, the permanent extension produced. If this does not exceed the specified value (usually $\cdot 1$, $\cdot 2$, or $\cdot 5$ per cent) the material has "proved" satisfactory.

The Maximum Stress (M.S.)

The maximum stress, or ultimate tensile stress (U.T.S.), is always calculated on the initial area of the test piece and not on the area at the point of fracture. It is used as the basis of almost every calculation involving stress, factors of safety being based on the tensile strength.

Elongation

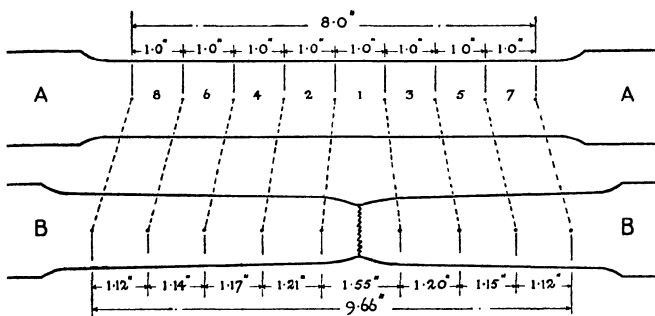
Fig. 6 illustrates diagrammatically the change of shape which a test piece undergoes as a result of the tensile test. "A" represents the specimen before testing, equal divisions being marked off on the parallel portion at intervals of 1 in. After fracture, the two parts of the test piece are placed together, and the distances between the marks remeasured (fig. 6 B). The elongation is expressed as a percentage of the original gauge length. It will be seen that the elongation is not uniformly distributed, being greatest near the point of fracture and least near the shoulders. The total extension is made up of two parts—the general extension, and the local extension at the point of fracture. The diagram explains the necessity of stipulating the gauge length when specifying or describing an elongation. It also indicates (fig. 6 C) that if a test piece were to break near the end, the elongation would be lower than would normally be obtained. Most specifications provide for this contingency by permitting a retest if the test piece breaks outside the middle half of the gauge length.

The Elongation is a measure of the ductility of steel. Generally speaking, a high tensile strength is accompanied by a low elongation, but by suitable choice of material and by heat treatment the tenacity may be raised considerably without detriment to the elongation.

Reduction of Area

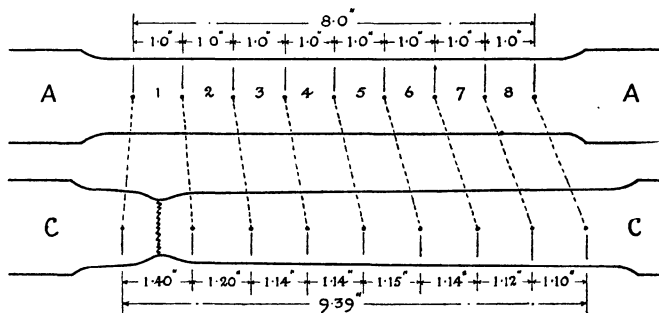
Just before rupture takes place, the test piece contracts at the point at which fracture occurs, and the reduction of area produced is expressed as a percentage of the original area. This property is a measure of the ductility and of the malleability of the material, and a high reduction of area indicates that the material is capable of being cold worked in all directions. The reduction of area, like the elongation, decreases as the tenacity increases, but here again suitable material and treatment may provide both a high tenacity and a high reduction of area. The reduction of area is seldom included in specifications unless when the material is supplied in the heat-treated condition.

The appearance of the fractured surface of a tensile test piece affords valuable information on the nature of the material,



EXTENSION ON 3 INCHES (1,2 & 3) = 32.0 PER CENT.

INCHES NO.	TOTAL EXTENSION.
1	0.55" = 55.0%
1 & 2	0.76" = 38.0%
1 TO 3	0.96" = 32.0%
1 TO 4	1.13" = 28.2%
1 TO 5	1.28" = 25.6%
1 TO 6	1.42" = 23.6%
1 TO 7	1.54" = 22.0%
1 TO 8	1.66" = 20.7%



EXTENSION ON 3 INCHES (1,2 & 3) = 24.6 PER CENT.

INCHES NO.	TOTAL EXTENSION
1	0.40" = 40.0%
1 & 2	0.60" = 30.0%
1 TO 3	0.74" = 24.6%
1 TO 4	0.88" = 22.0%
1 TO 5	1.03" = 20.6%
1 TO 6	1.17" = 19.5%
1 TO 7	1.29" = 18.4%
1 TO 8	1.39" = 17.3%

Fig. 6.—Elongation of Tensile Test Pieces

and may indicate the presence of flaws which might otherwise escape detection.

Typical fractures of tensile test pieces are illustrated in fig. 7 (Plate 2).

"A" shows the normal "cup and cone" fracture of ductile steel, while "B" shows the typical crystalline fracture of brittle material.

The dimensions of tensile test pieces do not influence the tensile strength, but in commercial testing the errors due to human factors are reduced when larger test pieces are employed. The larger the test piece, the more reliable and representative will be the results obtained.

There are occasions, however, when only a very small quantity of material is available, and to provide for this the Hounsfield Tensometer has been marketed. Tensile test pieces for this machine can be prepared from samples 1 in. long and $\frac{1}{2}$ in. square or round. Although the diameter of the test piece is only $\cdot 125$ in., the yield point, ultimate tensile stress, elongation and reduction of area values obtained are reliable.

The rate of strain does not appreciably affect the results obtained in tensile testing at ordinary temperature, but at high temperatures it is of paramount importance on account of the phenomenon of creep (see Chap. XI).

Bend Tests

Cold bend tests are a rough measure of the ductility of the material. They are supplementary to the tensile tests. It would be impracticable, on account of expense, to prepare a large number of tensile tests from each batch of material, while bend tests can be made cheaply. They ensure the detection of hard non-ductile material.

Temper bend tests are included in some specifications. It is commonly stated that the test piece should be heated to a "blood red" and quenched in water at a temperature not exceeding 80° F. But the temperature represented by "blood red" may have any value between 600° C. and 800° C. The temperature of quenching is of such great importance, as will be demonstrated later, that such vague expressions as "blood red" render the test useless from a practical view-point. What the test is intended to discover is by no means clear, and it has now been omitted from B.S. specifications.

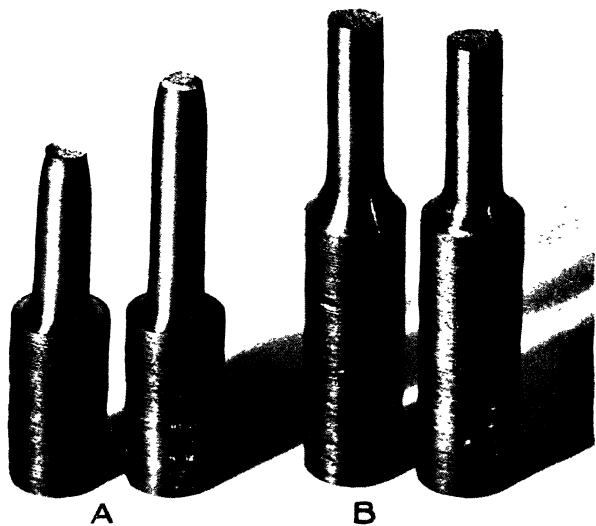


Fig. 7.—Tensile Test Fractures

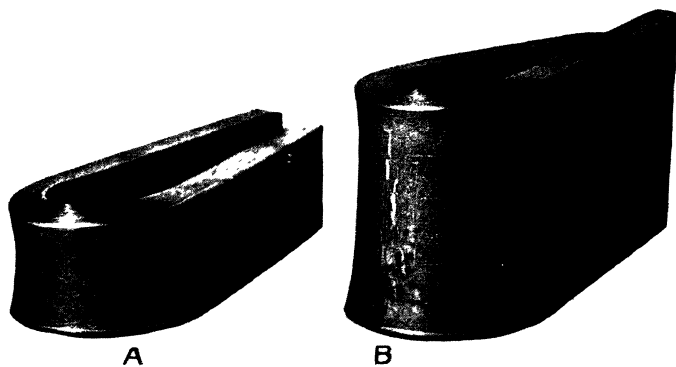


Fig. 8.— $1\frac{1}{2}$ in. and 3 in. Wide Bend Tests

Hot bend tests are carried out on wrought iron to detect red-shortness (i.e. brittleness at a red heat). The test piece is bent at a temperature between 930° C. and 980° C.

Nicked bend tests are also carried out on wrought-iron and steel for the purpose of examining the fracture. This test will be discussed later (p. 22).

The width of a bend test piece has a considerable effect on the results obtained. Most plate specifications provide for a test piece $1\frac{1}{2}$ in. wide, the bending radius depending on the thickness of the plate or section. With a wider test piece, fracture occurs more readily. This is shown in fig. 8 (Plate 2). The pieces A and B were cut from the same plate, and in the same direction. The width of A is $1\frac{1}{2}$ in., and that of B is 3 in. It will be observed that while A has bent satisfactorily, B has fractured.

Notched Bar Impact Test

This test is usually carried out on an Izod single-impact machine (fig. 9). The standard square test piece has the form shown in fig. 10, three notches being cut in each bar. The

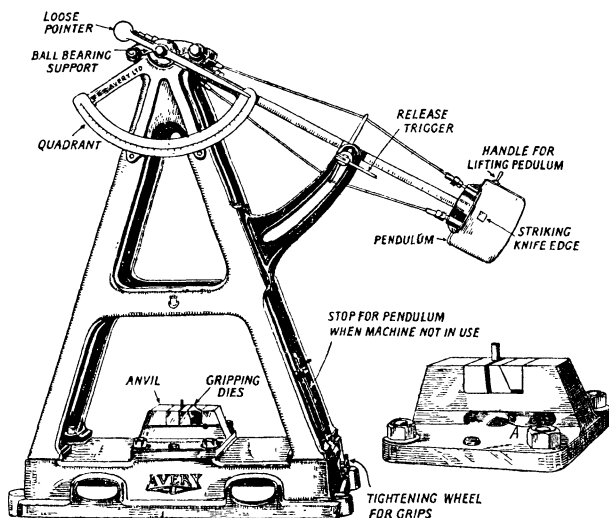


Fig. 9.—Izod Impact Testing Machine

machine is calibrated to indicate, in foot-pounds, the energy required to break the test piece. The area of the test piece below the notch is 80 sq. mm. ($= \frac{1}{8}$ sq. in. approximately);¹ the results are therefore sometimes reported in ft.-lb. per square inch. The values obtained from steel vary from practically zero to 800 ft.-lb. per square inch. The test is intended to be a measure of the toughness of the material, but impact tests on unnotched bars do not give comparative results. What the test does show is the resistance to the propagation

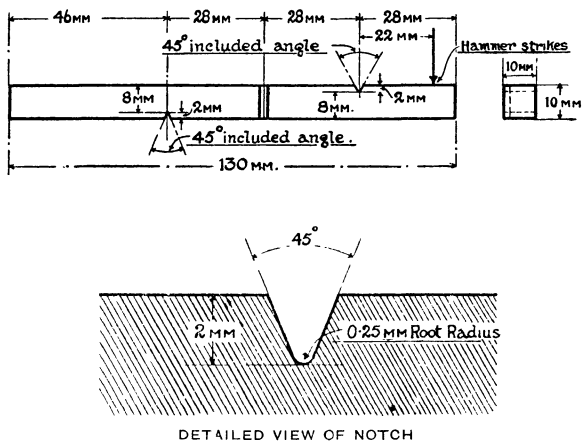


Fig. 10.—British Standard "Izod" Impact Test Piece

of a crack once formed, and this may be most useful information. Abrupt changes of section are not uncommon in engineering structures, and the danger of failure through cracking at sharp corners is considerable. The impact value bears no relation to the maximum stress except that, other things being equal, a high tensile value will be accompanied by a low impact figure. The impact value, more than any other property, depends upon the heat treatment (see Chap. VI). A very full discussion on the Notch Impact Test is recorded in *Transactions of the Manchester Association of Engineers*, 1937/1938, pp. 37-230.

¹ B.S. round test pieces (10 mm. dia.) have the same area below the notch.

The tensile, bend, and impact properties of steel depend to a considerable extent on the relation of the axis of the test piece to the direction in which the material has been rolled or forged. For example, a cross test from a rolled bar will give a lower maximum stress, and a much lower elongation and reduction of area than a test taken in the direction of rolling, while a cross impact test would give a very low value. These facts will easily be understood when the structure of the material is considered, and will then be fully discussed.

Hardness Test

This test affords a means of finding quickly and cheaply the approximate tensile strength of materials. The Brinell hardness tester is the machine most commonly used (fig. 11). A 10 mm. dia. ball of specially hardened steel is pressed on a ground or filed surface of the material, with a load of 1000 or 3000 kilograms which is maintained for not less than 15 seconds. The surface must be flat, so that the impression may be truly circular. The diameter of the impression is measured with a low-power portable microscope provided with a scale. A conversion table supplied with the machine indicates the Brinell hardness from the reading obtained under the microscope. The Brinell machine also employs balls of diameter down to 2 mm. and loads down to 4 Kg. The approximate tensile strength of steel may be found by multiplying the Brinell number by 0.23 for steels as rolled or annealed and by 0.22 for quenched and tempered steels.

The Diamond Pyramid Hardness tester (fig. 12, Plate 3) is the same in principle as the Brinell machine, but a diamond in the form of a square pyramid is used in place of a hardened steel ball. The diameter of the impression is read by means of a microscope incorporated in the machine, and Conversion Tables convert the diameter of the impression obtained to Diamond Pyramid Hardness numbers. Loads from 5 Kg. to

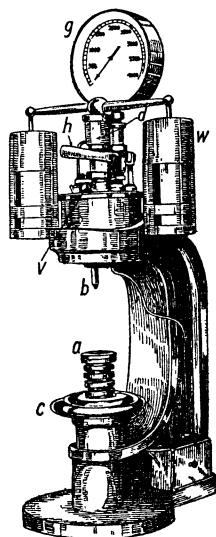


Fig. 11.—Brinell Hardness Testing Machine

100 Kg. may be applied. In reporting the results the load should be stated, e.g. $H_D/30 = 490$ indicates that a Diamond Pyramid Hardness number of 490 has been obtained with a load of 30 Kg. (B.S.S.¹ 427). The diameter and depth of the impression are very small, and many tests may be made over a small area. This is particularly useful in the examination of welds and in hardenability tests.

The Rockwell Hardness Tester (fig. 13, Plate 3) is somewhat different, the principle of this test being illustrated graphically in fig. 14.

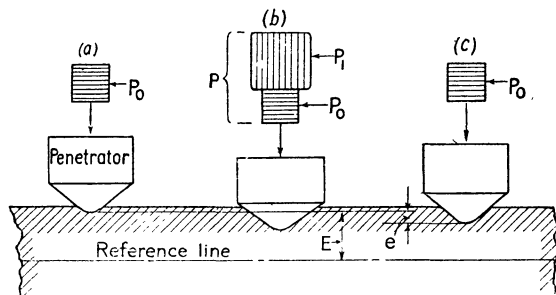


Fig. 14

A minor load is applied (a) to a penetrator and causes an indentation in the test specimen.

While the minor load is still operating, it is augmented (b) by a major load with resulting increase in the depth of indentation.

The major load is then removed (c), the minor load being still retained; this operation effects a partial recovery in the depth of the indentation as compared with (b), and eliminates the indication of the deflection in the structural members during application of the major load.

Two alternative forms of penetrator are used, (1) a diamond cone with rounded point, or (2) a hardened steel ball.

Rockwell Hardness numbers are read directly on the indicator shown in fig. 13.

Three scales are used: (A) diamond cone with total load of 60 Kg., (B) steel ball with total load of 100 Kg., (C) diamond cone with total load of 150 Kg.

¹ B.S.S. = British Standard Specification.

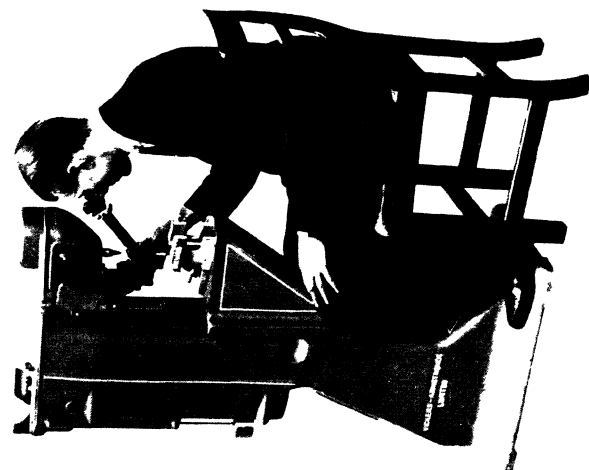


Fig. 12.—Vickers Hardness Testing Machine

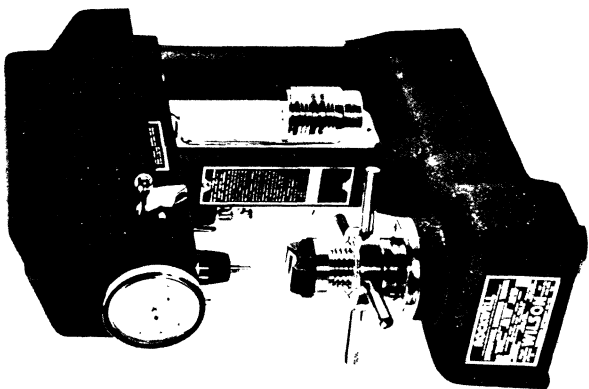


Fig. 13.—Rockwell Hardness Testing Machine

TABLE II
APPROXIMATE RELATION BETWEEN BRINELL, DIAMOND PYRAMID AND ROCKWELL HARDNESSES AND
TENSILE STRENGTHS OF STEEL

Brinell. (B.H.)	Diamond Pyramid H _D	H.C.	Rockwell. H.B.	Tensile Strength. Tons/sq. in.	B.H. or H _D	Rockwell. H.B.	Tensile Strength. Tons/sq. in.
627	765	60	—	139	223	97	50
578	675	57	—	127	212	96	47
534	598	53	119	118	202	94	45
495	540	50	117	109	192	92	43
461	494	47	116	101	183	90	41
429	454	45	115	94	174	88	39
401	420	42	113	88	166	86	38
375	389	40	112	82	159	84	36
352	363	37	110	77	153	82	35
331	339	35	109	73	146	80	33
311	316	33	108	68	140	78	32
293	296	31	106	64	134	76	30
277	279	29	104	61	128	73	29
262	263	26	103	58	124	71	28
248	248	24	102	55	118	69	27
235	235	22	99	52	112	66	26

In reporting the results it is necessary to state the scale to which they refer; for example, H.C. 40 indicates a Rockwell Hardness of 40 units determined on the (C) scale. (B.S.S. 891.)

A very convenient form of portable hardness testing machine is the Shore scleroscope. A diamond-tipped hammer drops by its own weight from the top of a graduated tube and the height of the rebound is read on a scale. The harder the test piece the higher will be the rebound. The surface of the test piece must be smooth and the instrument must be held or clamped in a vertical position. (A plumb rod is attached to the instrument.) The hammer is released by pressure on a bulb, and is returned to the top of the tube and fixed there by the same means.

The scleroscope hardness tester is reliable only for the harder grades of steel. It is specially suitable for the testing of case-hardened articles, dies, gears, and the like.

Table II shows the relation between the various hardness numbers and the tensile strength, but it must be emphasized that this relationship is approximate and applies only to steel.

Fatigue Tests

These are now more frequently specified than formerly. The Wöhler fatigue machine is the most convenient and economical (fig. 15). The test piece is in the form of a cantilever at one end of which the load is suspended. The test piece is rotated at a high speed, thus producing in it alternating compressive and tensile stresses ranging from zero to the maximum value. The fatigue range is that maximum alternating stress which when applied for an indefinite number of reversals will not produce fracture. The number of reversals usually applied is 6×10^7 . Several tests are required to determine the fatigue value, and the time required is considerable. Experience has shown that the fatigue range is closely related to the tensile strength and is approximately 80 to 90 per cent of that value. For example, steel having a tensile strength of 40 tons per square inch would have a Wöhler fatigue range of about ± 17 tons per square inch. Some specifications provide for a test being carried out at an arbitrary range of stress somewhat higher than the maximum for say 20,000 reversals. Such a test is easily and quickly performed.

Fatigue failures in service are almost always associated with

abrupt changes in section, and in most cases are due to local concentration of stress arising from the absence of adequate fillets. For the same reason fatigue cracks often have their origin at keyways, oil holes, &c., and in some cases the "stress raisers" are provided by the notch effect of too rough machining. It follows, therefore, that many textbook data on fatigue may be discounted in practice, since they are based on the results of tests on specimens with perfectly smooth surfaces, whereas the engineer is concerned with "notch sensitivity", data for which are provided by fatigue tests carried out on notched specimens.

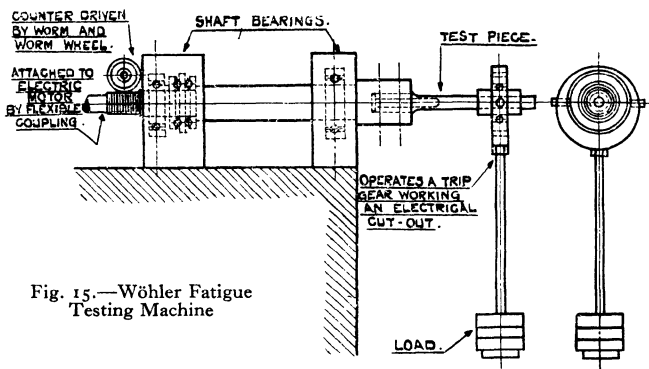


Fig. 15.—Wöhler Fatigue Testing Machine

Concentration of stress at notches or surface irregularities can be relieved by local yielding or plastic flow. Thus, steels with a low yield ratio often prove more reliable in service under conditions of alternating stresses than heat-treated steels with a high yield ratio, notwithstanding the fact that the latter have a higher fatigue range. In other words, if we wish to exploit the high fatigue range of the heat-treated alloy steels of high tensile strength and high yield ratio, then surface finish and the avoidance of stress raisers are of paramount importance.

Apart from irregularities of contour, the actual hardness of the surface also plays an important part in fatigue. There is obviously no advantage to be gained by using a high-tensile steel if the surface layers have been softened by decarburization, for it is the surface layers that carry the maximum stresses where there is bending. Conversely, the fatigue range can be

increased very appreciably by surface hardening as described in Chap. IX.

Another factor which has a profound influence in accelerating fatigue failures is corrosion. A notable example of this is to be found in ship propeller shafts, where sea water is the corrosive medium. This has led to the study of Corrosion fatigue, the tests being carried out as described above, except that during the test the particular corrosive solution under investigation is allowed to drip continuously on to the test piece.

CHAPTER II

The Structure of Ingot Iron and Wrought Iron

The extent to which the structure of a substance is revealed depends upon the physical or chemical means of differentiating between its constituents, and upon the degree of magnification which is employed in examining the visual results of that differentiation. Macro-structure is the structure revealed to the naked eye, micro-structure that revealed by means of the optical microscope, while atomic structure is revealed only by X-ray analysis. The limiting magnification of the optical microscope is about 1800 diameters, but this is more than adequate for most metallurgical purposes, magnifications in excess of 500 diameters being rarely employed. With the technique of selecting and preparing specimens of iron and steel for microscopic examination we are not here concerned, but a few observations may be made. First, since ferrous metals are opaque, even in very thin sections, they are examined by light reflected from a surface. This surface must be perfectly flat and have a high polish free from scratches. The polished surface is etched with a suitable reagent to "bring out" the structure, which should be observed with the naked eye as well as under the microscope (cf. figs. 16 and 21). For general purposes Nital, a solution of nitric acid in alcohol, is the most suitable etching reagent.

Chemically pure iron is not a commercial product. There



Fig. 16.—Ingot Iron. $\times 200$



Fig. 18.—Intra-crystalline Fracture in Mild Steel. $\times 250$



Fig. 19.—Inter-crystalline Fracture in Mild Steel. $\times 250$



Fig. 20.—Cold-drawn Iron Rod. $\times 200$



Fig. 21.—Section of Wrought-iron Bar. $\times \frac{1}{2}$



Fig. 22a.—Wrought-iron Bar. Length Section. $\times 350$

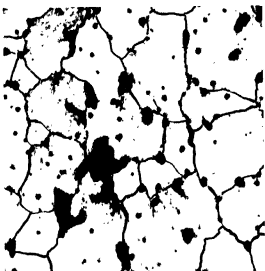


Fig. 22b.—Wrought-iron Bar. Cross Section. $\times 350$

are, however, some Swedish irons and a special grade of mild steel known as Ingot Iron which approximate closely to the pure metal and which therefore illustrate the simplest structural characteristics. The type of structure observed on examining a suitably etched specimen of ingot iron is shown in fig. 16 (Plate 4). Clearly, the metal is built up of an aggregate of very small units or cells, the irregular outlines of which have been revealed by the action of the etching solution. These cells form a network over the surface of the specimen. Each unit represents a section through a crystal grain of iron.

It may be somewhat difficult to realize that these grains are indeed true crystals, a crystal being commonly associated with geometric symmetry of outline. The absence of a symmetrical structure is explained by the manner in which the iron crystals are formed. When an ingot of molten iron cools down to the freezing temperature (about 1530° C.) solidification commences simultaneously at many points throughout the mass. At each of these points there is formed the nucleus of a crystal which, like all crystals, has a tendency to grow in certain well-defined directions. So long as perfect freedom is allowed, growth will proceed along these lines, but there soon comes a time when, owing to mutual interference between adjacent crystals, such freedom is restricted, with the result that the boundaries assume the polygonal outline seen in the micro-section. This is illustrated diagrammatically in fig. 17. Not only iron but all metals when examined under the microscope reveal the same type of structure. It is on this crystalline structure that the elastic properties of metals depend, for non-crystalline (i.e. amorphous) bodies do not possess such properties. That metals are crystalline in character is a fact which requires special emphasis, for there still are heard echoes of the fallacy that iron and steel crystallize in service when subjected to repeated stresses. Such views have arisen from the characteristic crystalline appearance of fractures which occur under these conditions, and which are known to be caused by a particular type of brittleness which is not due to any alteration in the structure.

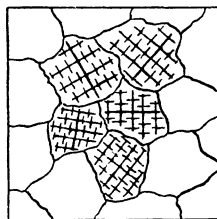


Fig. 17. — Illustrating Crystal Formation from Liquid.

On further examination of fig. 16 it might be thought that there would be a weakness at the boundaries of the crystal grains, and that when a piece of iron was tested in tension it would fracture by separation of the crystals. It has, however, been found from micro-examination that under normal conditions the path of the fracture invariably passes through the crystals, i.e. is "intra-crystalline" (fig. 18, Plate 4), and it is only in certain types of brittleness which may be produced in various ways that the fracture follows the boundaries of the grains, i.e. is "inter-crystalline" (fig. 19). Professor C. S. Edwards and Mr. L. B. Pfeil prepared single crystals of iron of sufficient size to enable a tensile test to be made. The remarkable fact was disclosed that single crystals have mechanical properties considerably inferior to those of an aggregate of small crystals of the same material. Some of their results are shown in Table III.

TABLE III¹

EFFECT OF CRYSTAL SIZE ON MECHANICAL PROPERTIES OF
ANNEALED IRON STRIP

Crystal Size (Number of Crystals per sq. mm.).	Limit of Proportionality. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation per cent on 2 in.
Single Crystal	2.0	10.0	33.0
6.3	2.89	15.03	35.25
15.3	2.77	16.33	47.0
51.0	4.5	17.37	44.75
75.5	8.98	18.73	47.0
120	7.44	18.40	42.5

The heat treatment of carbonless iron does not produce any marked change in properties. Even by the most drastic water quenching from a high temperature, the tensile strength of ingot iron is not raised by more than a few tons per square inch. There is, however, one method common to most metals whereby the properties of the material can be modified over a wide range, and that is by the application of cold work, as in the cold rolling of sheets and the drawing of wire. In the latter process, it is possible to raise the tensile strength of iron to a value as high as 45 tons per square inch, the normal value being about 22 tons. Such a change of properties always

¹ *Journal of the Iron and Steel Institute*, 1925, II, p. 95.

indicates some alteration in the structure. The change in structure caused by cold working is seen by a comparison between fig. 16 and fig. 20, the latter showing the structure of a longitudinal section of a cold-drawn iron rod. The forces applied in drawing the metal through the dies have had a very pronounced effect upon the crystals, and in place of the normal equiaxial form there is now considerable elongation in the direction of drawing. The most important observation to be made is that, although the crystals have been distorted, they still preserve their individual identity of outline.

Wrought Iron

The difference in composition between Ingot Iron and Wrought or Malleable Iron may be seen from the following typical analyses:

	Carbon. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	Manganese. Per cent.
Ingot Iron ..	.. '035	'01	'020	'001	'05
Wrought Iron ..	.. '03	'15	'025	'15	'03

Wrought iron contains a higher percentage of impurities, especially phosphorus and silicon, but the essential distinction between wrought iron and ingot iron is one of structure consequent upon the different processes of manufacture. Ingot iron is produced in the molten state and is cast into ingots in such a way as to ensure the most complete separation possible of all slag particles. The ingots after solidification and reheating are rolled or forged to the required section. Wrought iron, on the other hand, is produced in the puddling furnace, from which it is withdrawn in the form of pasty balls of metal, closely intermixed with considerable quantities of slag. Some of this slag is squeezed out and the metal consolidated by hammering, after which it is rolled into the crude flat bars known as "Merchant Bars". The merchant bars are cut up into convenient lengths, which are built up in layers or "piled". These in turn are heated to a high temperature and rolled to the required section, an operation by which the various layers or piles are welded together and the slag particles more or less regularly distributed in the form of elongated threads. This process of piling and re-rolling may be repeated, if desired, to promote greater regularity throughout the mass.

An interesting feature in the preparation of micro-sections of wrought iron is the way in which the various piles can be distinguished by the unaided eye after etching. This is due to slight differences in composition between the piles and is clearly shown in fig. 21. The arrangement illustrated is known as the Box Pile, since in its construction four flat bars are made to form the four sides of a box in which the other material is laid. By this means a bar is produced having a much more solid skin than can be obtained with an Open Pile. It can readily be understood that much useful information may be gained from such preliminary examination, since under the microscope the restricted field of vision does not permit of the above observations being made. The micro-structure of a typical sample of wrought iron is seen in figs. 22, *a* and *b*. It will be observed that the slag particles are embedded in a matrix of iron crystals which have the same appearance as those previously observed in ingot iron. As indicated above, wrought iron is less pure than ingot iron, but most of the silicon and phosphorus are present in the slag. Fig. 22 *a* shows a specimen cut in a length direction from a bar and reveals the slag particles elongated in the direction of rolling. On examining a section cut across the bar, i.e. at right angles to the direction of rolling, the slag appears as little round dots, showing that it exists in the form of threads (fig. 22 *b*).

It follows from the structure of wrought iron that it must possess decided directional properties, and that the tensile strength in the direction of rolling will be very much superior to that in a direction at right angles to it.

The nicked bend test provides a convenient means of examining the structure of wrought iron. The test piece "is lightly and evenly nicked on one side with a sharp cutting tool, and bent back at this point through an angle of 180° by pressure in a press or by a succession of light blows. It shall show a clean fibrous fracture, free from slag or dirt or any coarse crystalline structure."¹ A photograph of a nicked bend fracture is shown in fig. 23 (Plate 5).

Wrought iron is manufactured in various qualities which depend on the materials used in the puddling furnace, the method of piling the merchant bars, the number of times the piling, heating, and rolling processes are repeated, and upon the skill of the puddlers and heaters. To illustrate the difference

¹ *B.S.S.*, 51.



Fig. 23.—Nicked Bend Fracture of Wrought-iron Bar

in properties between the best and an inferior grade of iron, mechanical tests are appended showing typical results obtained from Best Yorkshire and from Grade C irons.

		Max. Stress Tons per sq. in.	Elongation per cent. B.S.T.P. "B ₁ ".	Reduction of Area, per cent.	B.S.S.
Best Yorkshire	..	22.0	35.0	58.0	858
Grade C	..	22.0	26.0	45.0	51

CHAPTER III

The Effect of Carbon on the Structure and Properties of Iron

The properties of carbon are greatly different from those of iron. It is to be expected, therefore, that more or less complex changes will take place when carbon is added to the metal, and that the resulting material, steel, will differ considerably from iron in its structure and properties. A study of this structure and these properties must therefore be preceded by an examination of the physical and chemical changes which take place when carbon and iron unite. These processes are best explained if we first consider an example of a similar but less complex reaction between two bodies when dissolved in one another.

The freezing-point of a pure substance is lowered when another substance is dissolved in it, and the extent of this depression is proportional to the quantity of the substance added. The temperatures at which freezing begins and ends are determined by means of cooling curves. These curves are obtained from temperature observations made at equal intervals of time by means of a thermometer or thermo-couple inserted in the cooling mass. Pure substances freeze at a constant temperature. For example, water freezes at 0° C., as is indicated by its cooling curve (fig. 24 A). The freezing-point is shown by an arrest in the cooling due to the evolution of latent heat. Fig. 24 B is the cooling curve of a solution of salt

in water and it shows two arrests. The first denotes the beginning of freezing and, as stated above, this occurs at a temperature lower than the freezing-point of pure water. The significance of the second arrest will be explained later. Arrests in the cooling curve are known as *critical points*. By obtaining a series of cooling curves from solutions of salt in water over a wide range of concentration, a Freezing-point Diagram, or, as it is more often called, a *Thermal Equilibrium Diagram*, may be constructed. Fig. 25 is the thermal equilibrium diagram for water-salt solutions.

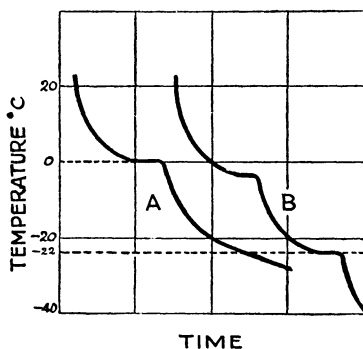


Fig. 24.—Cooling Curves of (A) Water and (B) Salt Solution

The line AEB represents the first arrest or critical point on each of the series of cooling curves. It shows that the freezing-point of water is progressively lowered by increasing amounts of salt until there is $23\frac{1}{2}$ per cent of it in the solution. For example, a solution containing 10 per cent of salt will begin to freeze at about $-9^{\circ}\text{C}.$, but it is *pure ice* which separates from the mixture, and the proportion of salt in the remaining solution is consequently increased. A further decrease in temperature is therefore necessary before more separation of pure ice takes place, and this produces a further increase in the concentration of salt in the solution. These processes continue alternately till, at the same instant, the remaining solution contains $23\frac{1}{2}$ per cent of salt and the temperature reaches $-22^{\circ}\text{C}.$ This solution then freezes without change of temperature. The process is similar if a 30 per cent solution is taken; here,

however, *pure salt* separates as the mixture cools, and the concentration of salt in the remaining liquid is progressively decreased till, as before, the concentration reaches $23\frac{1}{2}$ per cent salt at a temperature of -22°C. , when complete freezing takes place. Thus, whatever the concentration of the initial solution, freezing is completed at -22°C. This is the lower critical point indicated in fig. 24 B, and is represented in the thermal equilibrium diagram by the line CED. The diagram shows that a $23\frac{1}{2}$ per cent solution of salt in water has only one critical point, and its cooling curve therefore resembles that of

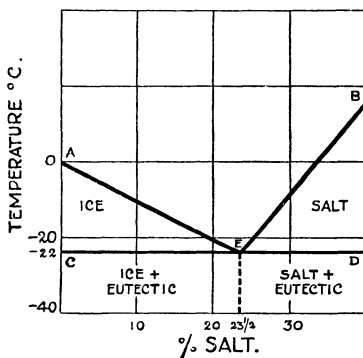


Fig. 25.—Water-salt Freezing-point Diagram

a pure substance. Its freezing-point is lower than that of any other salt-water solution, and for that reason it is called a *eutectic* (from a Greek word meaning "easily melted").

Ordinary solder, for example, is the eutectic of lead and tin, and contains 63 per cent of tin. The freezing-point of the pure metals and of the eutectic are as follows: lead, 327°C. ; tin, 232°C. ; eutectic, 180°C. Eutectic alloys with very low freezing-points can be obtained by mixing three or more metals in suitable proportions. The most fusible of such alloys at present known is Wood's Metal, which melts at 60°C. Its composition is: bismuth, 50 per cent, lead, 25 per cent, tin, 12.5 per cent, and cadmium, 12.5 per cent.

It must be clearly understood that eutectic alloys are simply mechanical mixtures, and that the phenomena above described take place only when the substances dissolve one another in

the liquid state and not in the solid condition. Fig. 26 illustrates diagrammatically the typical eutectic structure and shows that the eutectic consists of alternate layers of the constituent metals, which have separated in succession at a constant tem-

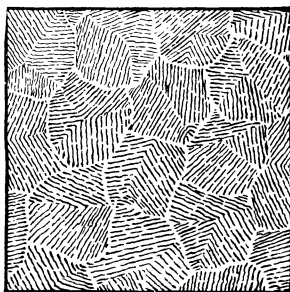


Fig. 26.—Typical Eutectic Structure

perature during the freezing of the alloy. Alloyed substances which remain in solution during solidification show a structure which is indistinguishable from that of the pure metal. Such alloys are known as solid solutions.

Allotropy

The freezing of a substance consists of a rearrangement of the particles or molecules of which it is composed. Liquids are without form; the molecules of solid bodies are arranged in a well-defined manner. They are crystalline.¹ But some solid bodies are capable of a molecular rearrangement in the solid state, and so may exist in two or more different forms possessing different properties. For example, carbon has three distinct solid forms, diamond, graphite, and charcoal. (These are the *allotropic* forms of carbon.) Tin has two, being transformed into a grey powder at a low temperature. Substances which can exist in two solid forms are called di-morphous. Iron is di-morphous, the transformation temperature being 900° C. On cooling to this temperature, gamma (γ) iron changes to alpha (α) iron, and this change is denoted in the cooling curve by a critical point. This critical point (called Ar_3) is lowered by the presence of another sub-

¹ Non-crystalline solid bodies are supercooled liquids, e.g. glass.

stance just as the freezing-point is lowered, and phenomena similar to those already described take place. Thus, as will be demonstrated later, it is possible to retain iron in the gamma condition at ordinary temperatures. The principal differences, apart from atomic structure, between gamma iron and alpha iron are that gamma iron retains carbon in solution and is non-magnetic, while alpha iron does not dissolve carbon appreciably and is strongly magnetic.

Iron and Carbon

Iron and carbon combine to form cementite (FeC_3)¹, which is completely soluble in molten iron, and is sufficiently soluble in gamma iron to give a concentration of from .9 per cent carbon at 700° C. to 1.8 per cent carbon at 1135° C. This solution of cementite in gamma iron is called *austenite*. Pure iron has its melting-point (1530° C.) progressively lowered by successive additions of carbon to 1135° C., at which point the eutectic alloy freezes. This eutectic contains 4.3 per cent of carbon, and consists of a mixture of austenite and cementite. As the temperature is further lowered the cementite is partially decomposed into graphite, the amount of which depends upon the carbon content and the other constituents (principally silicon) of the alloy. Alloys containing 2 to 3.5 per cent carbon are cast irons, which are beyond the scope of this book.

Let us now consider the changes which take place when austenite cools from a high temperature. Fig. 27, it will be seen, is similar to the freezing curves of water-salt solutions (fig. 25), and the changes which occur are essentially of the same nature as those which take place when such solutions cool. Take for example a steel containing .4 per cent carbon. This proportion of carbon depresses the critical point Ar_3 to 810° C., at which temperature *pure a iron*² (ferrite) comes out of solution. The remaining austenite therefore contains a higher percentage of carbon, and further cooling takes place before more iron separates from the solid solution. Finally, the remaining austenite containing .9 per cent carbon decomposes at 700° C. to a mixture of ferrite and cementite. This critical

¹ Cementite contains 6.7 per cent carbon, by weight.

² This is not strictly true, as alpha iron is capable of dissolving 0.035 per cent carbon, but this does not invalidate the arguments used. The effect of carbon dissolved in alpha iron is discussed in Chap. VI.

STEEL

point is known as Ar_1 . The mixture of ferrite and cementite is known as a eutectoid.

Fig. 29 shows the structure of a steel containing .47 per cent carbon, which has been slowly cooled to permit of the above described changes taking place. It consists of crystals of the eutectoid of ferrite and cementite embedded in a network of ferrite. The eutectoid, from its resemblance to mother-of-pearl, is known as *pearlite*. Normally the banded structure of pearlite is observable only at high magnification (fig. 30).

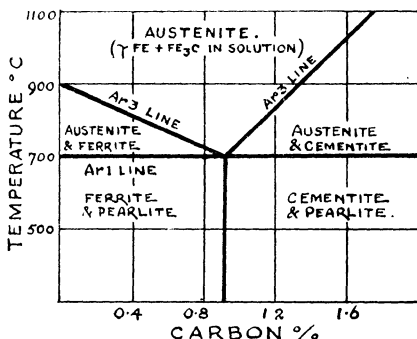


Fig. 27.—Iron-carbon Equilibrium Diagram

Pearlite, like any other eutectic, is an intimate mixture. Fig. 31 shows a steel of approximately eutectoid composition (carbon = .90 per cent), the structure being entirely pearlitic.

With a carbon content greater than this, the structure is similar to that obtained with less carbon, but the white network consists of cementite which has separated from the cooling steel. This is well shown in fig. 33, which represents the same steel as fig. 32, but the etching reagent used (boiling sodium picrate) has attacked the cementite, which therefore appears black against the unetched pearlite. Such steels are "*hyper-eutectoid*", while steels containing free ferrite are "*hypo-eutectoid*" (see figs. 28 to 30, Plate 6).

The Effect of Heat on Steel

The changes described above, which take place on cooling steel, are reversed on heating, with two important differences.



Fig. 28.—23 per cent C Steel as Rolled. $\times 200$

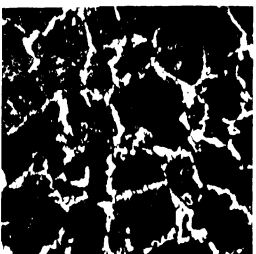


Fig. 29.—47 per cent C Steel as Rolled. $\times 200$



Fig. 30.—47 per cent C Steel as Rolled. $\times 500$

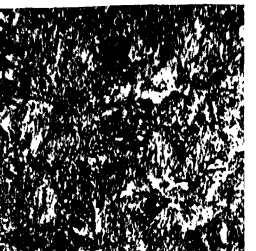


Fig. 31.—90 per cent C Steel as Rolled. $\times 200$

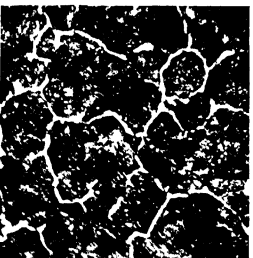


Fig. 32.—10 per cent C Steel as Rolled. $\times 200$

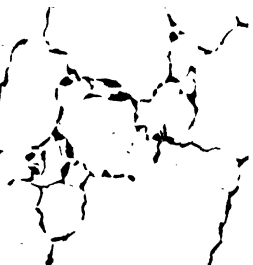


Fig. 33.—10 per cent C Steel as Rolled, Sodium Picrate Etch. $\times 200$



Fig. 40a.—Ghost Line in Rolled Steel. $\times 55$

The critical points on heating (called Ac_1 and Ac_3) occur at higher temperatures than the corresponding critical points (Ar_1 and Ar_3) observed on cooling. This effect is common to all critical changes produced by thermal treatment, and is of the utmost importance in heat treatment operations. Again, when the heating of steel is continued beyond the upper critical point (Ac_3), grain growth begins, and the crystals increase in size by absorption of or union with adjacent crystals. The extent of grain growth depends upon the time and the temperature. Longer times and higher temperatures increase the rate of growth, so that very coarse structures may all too easily be obtained. These large crystals result in a coarse structure on recooling, to the detriment of the desirable qualities of the material. For this reason, the proper heat treatment of steel is a subject which demands the closest attention, and is considered in detail in Chapter VI.

The Effect of Carbon on the Properties of Iron

We have seen that carbon lowers the melting-point of iron. This, in part, explains the fact that steel is more easily burned (see p. 148). Carbon also reduces the weldability of iron, and for that reason welding steels are usually specified with a low carbon content. The density of iron is lowered by the addition of carbon, but the effect is small, and in most applications is negligible. The compound of iron and carbon, cementite, is a hard brittle substance, and its presence increases the tenacity and reduces the ductility of iron. The relation between carbon content and mechanical properties is indicated in Table IV.

TABLE IV
EFFECT OF CARBON ON MECHANICAL PROPERTIES OF
PLAIN CARBON STEELS

Carbon. Per cent.	Yield Point. Tons/sq. in.	Maximum Stress. Tons/sq. in.	Elong. per cent on 2 in.	Red. of Area. Per cent.
0.10	15.0	25.0	38.0	67.0
0.20	18.0	30.0	32.0	60.0
0.36	21.0	38.0	25.0	50.0
0.50	24.0	45.0	20.0	38.0
0.60	28.0	52.0	16.0	28.0
0.80	33.0	60.0	11.0	16.0

Other factors, as will be seen later, have profound effects on the tensile properties, but in the steels shown in the table these factors are constant, and the variation in properties is due to carbon content only. But the most important and far-reaching effect of carbon on iron is that of rendering the metal peculiarly susceptible to variations in the rate of cooling from a high temperature. Wrought iron is not appreciably hardened by the most drastic water quenching, while by the same means steel may have its tensile strength increased by 50 tons and upwards.

Other Constituents of Carbon Steels

The equilibrium diagram (fig. 27) is not altered to any appreciable extent by the presence of manganese, silicon, sulphur and phosphorus in the proportions usually occurring in plain carbon steels. Of these elements manganese is the only one which forms carbides, and a portion at least is always combined with the pearlite, thus increasing the amount of that constituent as seen in the microstructure. It follows, therefore, that manganese has an important influence in increasing the tenacity of steel. At the same time it improves the notch toughness as measured by the Izod Test. Silicon, on the other hand, is present in solution in the ferrite, except that portion which exists as entrapped silicate slag particles. Unlike manganese and silicon, which are beneficial to the steel, sulphur and phosphorus are regarded as undesirable impurities, and as such they are usually restricted by specification to .05 per cent. There is an exception in that sulphur is sometimes intentionally added to steel to improve its machining properties (see p. 75). The effect of other alloying elements is considered in Chaps. VI and VIII.

The magnetic properties of iron are changed by alloying with carbon. Iron is easily magnetized, and as easily loses its magnetism. Steel, especially if the carbon is high, is more difficult to magnetize, while, on the other hand, with suitable heat treatment it makes a good permanent magnet. All steels are non-magnetic above the Curie Point (768°C.).

Many empirical formulæ have been devised to enable the tenacity of commercial plain carbon steels to be estimated from the analysis. The following example has been constructed by the authors and is reliable within a restricted range:

$$17 + 50\text{ C} + 10\text{ Si} + 4\text{ Mn} = \text{tons per square inch.}$$

C, Si, and Mn represent the percentage of carbon, silicon, and manganese in the steel. The formula indicates the relative effects of these elements, and also that pure iron would have a tenacity of 17 tons per square inch.

The above formula is applicable only to material in the normalized condition with carbon, silicon, and manganese contents not greater than .4 per cent, .3 per cent, and 1.0 per cent respectively. Within these limits are included practically all the carbon steels used in general engineering work with the exception of tool steels.

CHAPTER IV

The Manufacture of Steel—Steel in the Ingot Stage

The Siemens-Martin Open-hearth Process is generally the most economical method for the manufacture of modern engineering steels, and is therefore responsible for by far the greatest portion of the world output. On the Continent and in America the older Bessemer or Thomas Process is responsible for a large and important tonnage, while recent years have witnessed an interesting and enterprising revival of the process in this country. Mention may also be made of the Crucible Process for the manufacture of high carbon tool steels and cutlery, and also of the Electric Furnace, the introduction of which within recent years has led to rapid developments in the field of alloy steels, including the wonderful range of stainless steels. It is outside the scope of this book to describe in detail any of these processes, which have been fully dealt with in the many excellent textbooks on the subject. For our purpose it is proposed to confine attention to a brief survey of the open-hearth process in the hope that this will lead to an intelligent understanding of the structure and properties of steel in general.

The Open-hearth Process

This is divided into two categories according to the grade of pig-iron used. Hematite pig-iron is made from high-grade

ores, and contains a low percentage of phosphorus. The refining of this iron is carried out under a slag having a high content of silica which is acid in character, consequently the furnace must be lined with an acid refractory material to prevent chemical reaction between the molten bath and the furnace hearth. Under such slag conditions phosphorus cannot be eliminated, and since this element seriously affects the properties of steel, it follows that in the acid process only raw materials containing low percentages of phosphorus can be used. The other grade of pig-iron, known as basic pig-iron, is made from ores which may contain as much as 2 per cent of phosphorus, and when dealing with this material it is necessary to refine under a slag containing a high percentage of lime which is basic in character, for it is only by this means that the phosphorus can be removed. The furnace lining is also basic, and the product is known as "basic" steel.

There has always been much controversy among engineers as to the relative merits of *Acid* and *Basic* steel. The fact that the basic process was introduced to deal with iron made from low-grade ores has certainly influenced prejudice against it, and it must be admitted that the bulk of the cheaper grades of steel are made by this process. At the same time it is a fact that with the best modern practice, basic open-hearth steel is being produced of a very high standard of quality.

The open-hearth furnace has usually a capacity of about 65 tons, although furnaces having capacities of 100 to 200 tons are in operation. The raw materials used consist essentially of a mixture of pig-iron and scrap along with the necessary fluxes for the creation of a suitable slag. The proportions of pig and scrap can be varied over quite a wide range without affecting the quality of the steel produced.

Consider a basic charge consisting of 60 per cent scrap with 40 per cent pig-iron of the following composition:

	Carbon. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	Manganese. Per cent.
Mild Steel Scrap	·15	·03	·05	·05	·50
Basic Pig-iron	3·5	·80	·05	1·5	2·0

Then the average composition of the metallic charge will be approximately:

Carbon. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	Manganese. Per cent.
1·5	·35	·05	·65	1·0

In the process of refining, the sulphur and phosphorus have to be eliminated as far as possible, while the carbon, silicon, and manganese have to be reduced to the percentages required in the finished steel. When the bath is molten the metal lies on a shallow saucer-shaped hearth under a covering blanket of slag. The removal of the impurities is effected by means of oxidation, part of the oxygen being supplied from the scale formed during the melting-down period, and the balance from ore additions to the molten slag. The oxide of carbon, being a gas, escapes in bubbles, and when these appear over the surface of the slag the bath is said to be "on the boil". The oxides of manganese, silicon, and phosphorus, on the other hand, pass into the slag, in which they are held. The process is controlled throughout by chemical analyses of small spoon samples of the metal drawn off at intervals, and the carbon is reduced to the amount required in the finished steel. Sometimes the carbon is reduced beyond this amount and it thus becomes necessary to recarburize at a later stage. In the basic process all the silicon and most of the manganese are unavoidably eliminated, because these two elements have a high affinity for oxygen.

The removal of impurities by oxidation is typical of all steel smelting processes, but unfortunately it is not possible to protect the molten iron from oxidation at the same time. Part of the oxide of iron so formed passes into the slag where it is lost, but what is more important is that part of the oxide remains in solution in the iron. Now it is essential for the production of sound steel that this oxide be removed as completely as possible before the steel is cast. The deoxidizing operation is known as "killing" the metal. Improperly killed, i.e. overoxidized, steel is said to be "wild" in casting from its turbulence in the ingot moulds. This is caused by the evolution of gas formed by the interaction of the oxide with the carbon in the steel in the same manner as occurs during the "boil" in the furnace. Such an evolution of gas occurring during the solidification of the steel in the moulds will obviously give rise to the formation of gas-filled cavities or "blow-holes". If the metal is badly overoxidized the resulting ingots will be unworkable, but fortunately such an occurrence nowadays is very rare. On the other hand, deoxidation may have been carried far enough to give an apparently sound ingot, but not far enough to prevent the formation of small

blowholes dangerously near the skin of the metal. These skin blowholes may be responsible for a type of surface defect in the finished steel known familiarly as "reeds". Most users of steel will have encountered reedy steel at some time or other, and may have observed that, as a rule, the softer the quality the more liable the steel seems to be to this trouble. That this should be so can be understood from the fact that the lower the carbon the greater is the degree of oxidation in the bath and therefore the greater is the difficulty in getting rid of the oxygen in the final stages.

When the furnace is tapped the metal and slag are poured into a large ladle, from which the metal is subsequently cast into the ingot moulds through a specially prepared nozzle fitted into the base of the ladle. Separation of slag from metal takes place in the ladle; the lighter slag, floating on the metal, protects it from oxidation and loss of heat.

The principal agents used in the deoxidation of steel are manganese, silicon and aluminium. In the acid process the first two may be added either to the furnace or to the ladle, while aluminium is added to the ladle or ingot mould. Aluminium is the most powerful deoxidiser used, and the normal addition is a few ounces per ton of steel. In general it is used in conjunction with silicon. Larger additions of aluminium, up to 2 lb. per ton of steel, are added for the purpose of producing "fine-grained steel" (see Chap. IX).

Besides acting as a deoxidizer, manganese plays an important part in counteracting the evil effects of the sulphur, which cannot be entirely removed in the refining process. The beneficial effect of manganese on the properties of steel in this respect is explained by the remarkable difference in behaviour between the compounds, iron sulphide and manganese sulphide, when present in the metal. In the absence of manganese, sulphur combines with some of the iron to form iron sulphide, which forms a very brittle membrane around the boundaries of the crystal grains. It is easy to see that where such a membrane exists the crystal grains will be easily separated when stressed: in other words, the metal will be dangerously brittle. If, however, there is sufficient manganese present in the iron the sulphur will attach itself to this element in preference to the iron, forming manganese sulphide, which separates out on solidification in the form of minute globules throughout the mass of iron; thus the ductility of the metal is not affected.

PLATE 7



Fig. 35.—Etched Cross-section of Ingot. $\times \frac{1}{4}$

Having outlined the main points concerning the refining of steel, we may now discuss the casting of the metal from the ladle into ingot moulds. It is now too late to rectify the faults of bad furnace conditions, but it is not too late to spoil what up till now may be perfectly good steel: in other words, the casting of the ingot calls for just as much care and attention as the preceding operations. It is a fact that most of the troubles experienced in the manipulation or service of steel can be traced back to some irregularity in the ingot, and it is desirable therefore that the engineer should have some knowledge of the principles involved in casting.

Casting of Steel

Ingot moulds are almost universally made of cast iron, having considerable wall thickness in order to withstand the severe conditions of service. The common shape is rectangular since this is the most convenient for subsequent working to shape in the rolling mills. For forging purposes, on the other hand, an ingot having a round section is often desirable, but owing to the severe stresses set up in the cooling of a round ingot, with consequent tendency to cracking, it is customary to use an octagonal or similar section.

To enable the ingot to be stripped from the mould after solidification, the mould is made open at both ends and is tapered in section. When casting, the bottom of the mould is sealed by simply placing it on a cast-iron base plate.

There are certain conditions in casting which should be observed. One of the most important of these is the temperature of the metal, the range of which is limited by the fact that if it is too high the ingots are liable to develop cracks in working, and if it is too low the metal is so sluggish that the ingot has a very uneven skin. With proper melting conditions in the furnace there should never be any lack of heat for casting; on the contrary the metallurgist is usually concerned with the problem of reducing the temperature during casting. Another equally important factor in casting is the prevention of "splash", that is the metal splashing on to the sides of the mould. Considering the head of metal in the ladle and the height the stream has to fall into the mould, it will be easily understood that to overcome splashing is by no means an easy matter, especially at the base end of an ingot when the stream strikes the bottom of the mould. Splashed metal

immediately solidifies on the cool mould walls and becomes coated with a film of scale which prevents it from becoming properly fused into the main body of rising metal. This gives rise to surface defects in the ingot, which are more often than not found later in the finished section. (See Chap. XIII.)

Top casting direct from the ladle to the mould (fig. 34 A) is the usual method for all ordinary steels, and, generally speaking, the finer and more uniform the stream the better will be

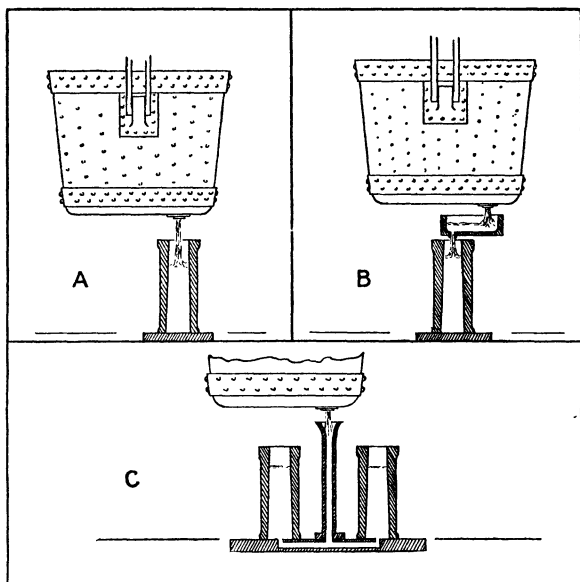


Fig. 34.—Methods of Casting Ingots

the resulting ingots. Sometimes a small trough-shaped vessel called a “tundish” or “bakie” is introduced between the ladle and the mould (fig. 34 B). This device reduces the force of the stream due to the head of metal in the ladle, thus minimizing splash, and at the same time it helps to reduce the temperature of the metal.

Bottom casting, in which the metal is fed through a system of refractory runners into the base of the mould (fig. 34 C), has

many advantages. In the first place it eliminates splash, and secondly the method is suitable for the simultaneous casting of a group of ingots from the one ladle stream.

Solidification of the Ingot

The conditions governing the solidification of ingots are not affected to any extent by the method of casting, whether from the top or bottom. In either case the steel fills the mould from the bottom upwards and cooling takes place by conduction of heat through the walls of the mould. When the molten steel first comes in contact with the mould there is a sudden chilling effect which results in the formation of a thin skin of solid metal. Owing to rapid freezing of this layer there is no time for the metal to take up any well-defined crystalline form. The mould, however, soon becomes heated and expands, causing the formation of an air-gap which greatly reduces the rate at which heat is extracted from the interior, so that the steel as it solidifies is given sufficient time to assume its characteristic crystals. The cooling conditions are now such that those crystals which form at the inner boundary of the chill skin grow inwards in a direction almost at right angles to the cooling surfaces of the mould. Lateral growth is prevented by the interference of adjacent crystals which are growing simultaneously, and so there is formed a zone of columnar crystals, shown in the etched cross-section of an ingot (fig. 35, Plate 7). As the growth of these columnar crystals proceeds, the remaining liquid metal in the interior is gradually losing heat, and there comes a stage when its temperature is so near to its freezing-point that solidification commences simultaneously throughout the mass by the formation of myriads of crystal nuclei which have freedom to grow in all directions. This leads to the formation of a zone of equiaxial crystals which are quite visible in the etched section (fig. 35). Thus is completed the solidification of the ingot, which therefore consists of three zones of crystals of different form. On the outside there is a thin skin of rapidly chilled metal which possesses no visible crystalline character. This is followed by a zone of columnar-shaped crystals at right angles to the cooling surfaces, and lastly there is a zone of equiaxial crystals.

There are two important observations to be made concerning the crystalline structure of the ingot. Firstly, the slow cooling is favourable to crystal growth, with the result that the structure

of the ingot is visible after etching without the aid of a microscope. Secondly, it will be noticed from the ingot section (fig. 35) that the columnar crystals growing inwards from the four surfaces meet along diagonal planes at the corners of the ingot. The existence of these planes constitutes a source of weakness which can be quite easily explained. As the crystals grow into the liquid interior, they reject any particles of slaggy matter and other impurities which happen to be present in the

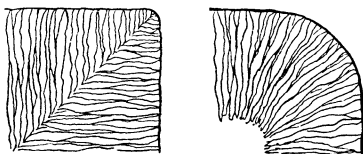


Fig. 36.—Influence of Mould Corners on Crystals

steel. It will be evident therefore that there will be a tendency for these impurities to become entrapped along these planes when the crystals meet. Sometimes the presence of these planes of weakness leads to the development of corner cracks during the rolling or forging of ingots. Much can be done, however, to reduce this trouble by having rounded corners on the ingot moulds, and the effect of this on the growth of these columnar crystals is clearly illustrated in fig. 36.

Contraction Cavities—Formation of “Pipe”

The volume changes which take place as the molten steel cools down and solidifies in the mould are unfortunately responsible for many of the steel-maker's troubles. Since solid steel is more dense than liquid steel it follows that during solidification there must be considerable volume shrinkage, which in an ordinary ingot leads to the formation of a characteristic cavity referred to as “Pipe”. This is illustrated for the simplest type of ingot with parallel sides in fig. 37 A. This diagram represents the progressive solidification of imaginary layers of metal from the outside inwards. The shrinkage which accompanies the solidification of the first layer results in a fall in the level of the molten metal in the interior, and the process may be visualized as repeating itself in successive stages, the level of each layer being lower than that of the preceding one due to the continued shrinkage. In this manner a central cavity

or pipe is formed, the only difference in practice being that the process is continuous instead of intermittent in layers.

It has already been explained that moulds are always made with tapered walls so as to enable the ingot to be stripped. There are two types of such tapered moulds in use. In the more common type the narrow end is at the top since this facilitates handling in the casting pit. In the other type the wide end is to the top, and this is sometimes referred to as an inverted mould. The solidification of metal cast into these two types of moulds is illustrated diagrammatically in figs. 37 B

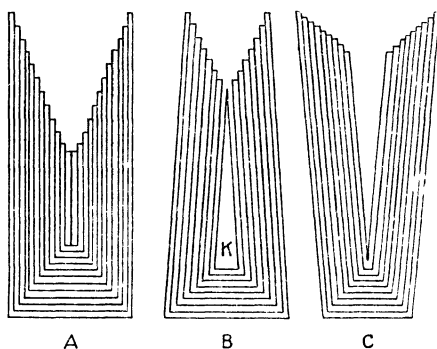


Fig. 37.—The Effect of Mould Design on the Solidification of Ingots
(after Brearley)

and C. It will be seen that, in the case of mould B with the narrow end up, there comes a stage in the process of freezing when there is a triangular area K which is still molten, but which is completely enclosed owing to the freezing over of the metal at the top. Now on further cooling the molten metal filling this area will eventually freeze also, but in doing so there will be shrinkage cavities formed which are quite distinct from the main shrinkage cavity or pipe at the top of the ingot. These secondary cavities are known as "Secondary Pipe". In mould C, fig. 37, with the wide end at the top, the formation of secondary pipe is prevented because the shrinkage is all the time being made up by the feeding down of molten metal from the top.

In the above discussion certain factors such as the cooling

effect of the air on the top surface of the ingot have been neglected, for the intention has been to give as simple an outline of the process as possible. It will be seen, however, from what has been described, that the mould with the wide

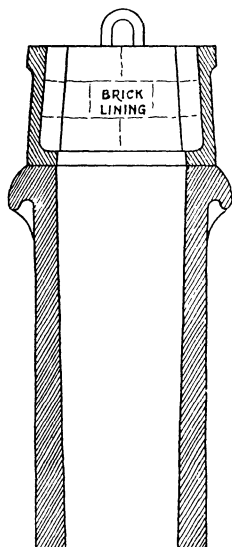


Fig. 38.—Ingot Mould with Brick Head

end at the top is more likely to give a sound ingot than the mould with the narrow end at the top, especially when the former is provided with a brick head as described below.

Anything in the nature of secondary pipe must be regarded as a dangerous flaw when dealing with special quality steels; dangerous because it is hidden and therefore not removed with the usual discard in rolling. For this reason such steels are always cast into ingot moulds having the wide end at the top.

In the production of sound ingots there have been various methods suggested for the elimination of pipe, but of these only one is practised generally; this consists of the introduction of a brick-lined head on the top of the inverted taper ingot (fig. 38). This head acts simply as a reservoir of metal which is kept molten till the last by the heat insulating properties of the brick lining. The presence of this head ensures a constant supply of

liquid metal which feeds down into any contraction cavities forming in the ingot. It should be observed that the better quality steels, such as those used for boiler plates, &c., are usually cast in this type of mould with brick head.

Chemical Heterogeneity—Segregation

Molten steel when it enters the ingot mould is a homogeneous solution, the various elements carbon, silicon, manganese, &c., being dissolved in the molten iron. The laws governing the solidification of solutions, particularly with regard to the depression of freezing-points or critical points, have already been referred to when discussing the iron-carbon equilibrium diagram (see Chap. III). It was shown that

the changes which take place in the solid solution of carbon in iron (austenite) were analogous to the changes which occur in the solidification of a solution of salt in water. Here for our purpose it is convenient to compare the solidification of a similar salt-water solution with the solidification of the molten steel solution with particular reference to the selective action which gives rise to chemical heterogeneity. It will be remembered that the freezing of a salt solution containing less than $23\frac{1}{2}$ per cent salt takes place over a range of temperature, and that the first crystals which separate out consist of pure ice, so that as freezing continues the remaining liquid becomes progressively richer in salt. In the same way the molten steel solution freezes over a range of temperature, but the selective action with regard to the first crystals formed is not so pronounced because of the fact that solid iron can hold a certain amount of carbon in solution. Without going into details it may be stated that at any given stage during the solidification of a mass of steel the particles which separate out and arrange themselves in ordinary crystalline formation are purer in composition than the remaining molten metal. Moreover as the temperature falls and freezing continues there is a progressive enrichment in carbon, &c., of both the solid particles which separate and the remaining molten metal. This factor has a profound influence on the character of ingots, for it results in segregation of the various elements in solution in the last part of the ingot to solidify, that is, in the vicinity of the pipe.

In an investigation carried out by a committee of the Iron and Steel Institute on "The Heterogeneity of Steel Ingots"¹ a number of ingots representative of ordinary modern practice were subjected to critical examination. The procedure adopted was to cut the ingot longitudinally along the central axis and determine the composition of drillings taken at various positions over the surface of the section. From the results obtained a table was compiled which clearly shows the degree of segre-

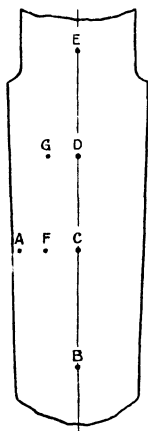


Fig. 39

A diagrammatic indication of the positions in the ingots selected for a comparison of the distribution of the elements.

¹ *Journal of the Iron and Steel Institute*, 1926, I, p. 39 et seq.

gation of the different elements, carbon, silicon, sulphur, phosphorus, and manganese, at certain selected points (see fig. 39 and Table V). The ingots dealt with were all cast in moulds having the wide end at the top and having brick heads. To quote from this report: "An examination of the figures in the table will show that in general the order of the several chosen positions as regards increasing concentration of the

TABLE V

AVERAGE COMPOSITION OF NINE REPRESENTATIVE INGOTS AS SHOWN BY ANALYSIS OF DRILLED SAMPLES AT THE SELECTED POSITIONS SHOWN IN FIG. 39

The figures for the various elements are expressed as a percentage of the amount of all the elements as ascertained by analysis of the corresponding test ingot.

Position in the Ingot as defined in fig. 39.	Average Figures for all the Nine Ingots					
	C.	Mn.	Si.	S.	P.	All Elements.
E.	141.8	103.9	107.7	148.8	134.8	127.4
G.	112.1	103.4	101.8	115.1	118.4	110.2
D.	106.8	100.9	101.8	114.2	108.7	106.5
F.	104.6	100.7	104.2	101.3	106.0	103.4
A.	103.8	100.6	100.7	99.0	104.0	101.6
Amount of the element contained in the test ingot.	100	100	100	100	100	100
C.	94.7	97.7	101.3	88.0	93.8	95.1
B.	85.7	97.2	103.0	76.6	86.7	89.8

five elements is B, C, A, F, D, G, and E. B usually contains the smallest amount of each element, and E in every case the largest. In individual cases the order varies somewhat but not greatly. Upward along the axis line the concentration increases from B progressively through C and D to E at the top of the ingot, where the greatest concentration of elements is found. The greatest heterogeneity is shown by sulphur. Carbon and phosphorus give figures more or less parallel with one another, but with a rather less range of variation than that of sulphur. Silicon and manganese on the other hand are shown to be not markedly segregating elements, a fact which is probably due

PLATE 8

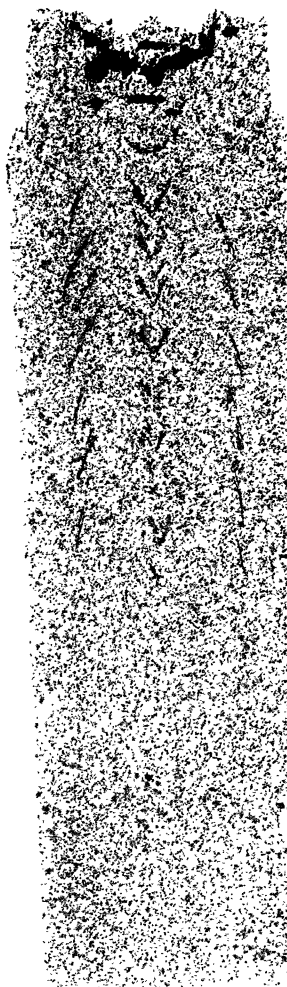


Fig. 40.—Sulphur Print of Sectioned Ingot

to their ready diffusion. It should be noted that the figures are derived from analyses made on drilled samples, and that therefore they cannot be expected to exhibit the actual extremes of concentration of the various elements, since segregated and non-segregated areas may easily be covered by the drill."

In the foregoing discussion on the characteristics of the steel ingot the broad facts have been presented as simply as possible. There are, however, several other factors, which are still the subject of investigation, and which have an important effect on the location of what may be termed local segregates. These local segregates can best be examined by the method of sulphur-printing as described on page 142. To examine an ingot by this means it is necessary to prepare a longitudinal section through the axis. A typical sulphur-print taken from such a section is shown in fig. 40. It will be observed that the dark areas which denote the presence of segregate appear in the form of strings which have a definite formation along the axis; these are arranged in the form of a "V", while the outer group are inverted "Λ". These local segregates give rise to structural irregularities, known as *ghosts*, in the finished steel (see fig. 40a, Plate 6).

Slag Particles in the Ingot

The chemical reactions which take place during the refining of steel in the furnace, and in the ladle when manganese or silicon additions are made for the purpose of deoxidation, cause the metal to become impregnated with minute particles of slaggy matter consisting mostly of silicates of iron and manganese along with manganese sulphide, which are the products of these reactions. Complete separation of these by letting them rise to the surface could be effected only if the molten steel were kept undisturbed in a state of chemical equilibrium for a considerable time. In practice, however, such ideal conditions are never attained. Some separation does occur not only in the furnace after the boil is over, and in the ladle during the waiting period, but also in the mould. Against this, however, there are oxidation of the metal stream during casting, giving rise to fresh iron oxide which reacts again with the manganese and silicon, and also the additional reactions between the metal and the refractories with which it comes in contact, all of which create particles of slag. It follows, therefore, that so long as steel is manufactured in

this way the presence of minute slag particles cannot be avoided, and it is well that this should be borne in mind when examining specimens under the microscope. At the same time this should not be accepted as an excuse for dirty steel, for it is possible by careful control in the melting shop to produce steel which, all things considered, is remarkably clean.

In the ingot the slag particles and other non-metallic inclusions exist in the form of globules which are subsequently distorted in the rolling or forging processes after the manner of the slag in wrought iron previously referred to (p. 22). It is often found that inclusions in steel are associated with decarbonized areas or "ghosts", an example of which is shown in fig. 41 *a* and *b* (Plate 9). Note that etching is not necessary for the detection of inclusions in the metal; it is always advisable, therefore, to carry out a preliminary micro-examination of the polished specimens before developing the structure. So far as they concern the engineer, inclusions in steel may be regarded as possible locations of stress concentrations. Consequently their presence is undesirable in parts which are subjected to severe stresses, particularly where these are alternating. For the same reason inclusions are a cause of cracks in quenching operations and in the case-hardening process. The effect of inclusions on the directional properties of hot-worked steel is discussed in the next chapter.

CHAPTER V

The Hot Working of Steel

The hot working of steel comprises the operations of rolling, forging, drop forging or stamping, and pressing. Rolling or forging may be carried out direct from the ingot, while the other operations are performed only on steel which has previously undergone some other form of hot work.

Heavy bars and sections for machining and structural work are rolled in a Bar or Section Mill. The ingot after stripping from the mould is transferred to a reheating furnace where it is heated to a temperature of from 1000° to 1250° Centigrade,

according to the type of steel and the amount of work which has to be put on it. When well soaked at these high temperatures, steel is plastic and can be readily worked to any desired shape. The plasticity increases with increase in temperature, and for this reason it is necessary for the temperature of the ingot to be uniform throughout, otherwise trouble will be experienced in the mill. Bar and section mills are provided with grooves, or "passes" as they are termed, cut in the rolls. The metal is drawn through these grooves by the rotation of the rolls, and by a series of such passes is reduced to the required section. A typical roll train illustrating successive passes is shown in fig. 42. The design of the grooves

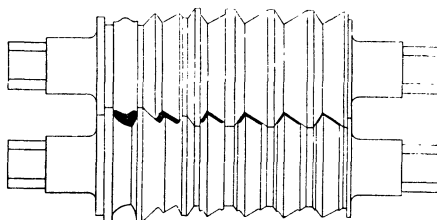


Fig. 42.—Roll Train for Angles

in the rolls is of the utmost importance, for bad design leads to defects in the finished material. We are not here concerned with the details of rolling-mill practice; it is sufficient for our purpose to observe that in the rolling of bars and sections the ingot is worked in one direction only, being elongated in the direction of the major axis. The significance of this will be referred to later.

In rolling plates it is the general practice first to reduce the ingot to a slab in a Cogging or Slabbing Mill. The cogging mill, like the bar mill, elongates the metal in one direction only, forming a long slab which is sheared hot into smaller lengths. These are reheated to a uniformly high temperature before transfer to the Plate Mill. The plate mill is provided with plain cylindrical rolls, without grooves or passes, so that the edges of the slab do not come in contact with a roll surface. The forces operating on the slab as it is drawn between the rolls are, however, such that it is elongated while the width remains practically constant. In other words, there is no lateral spread of the

metal. We find therefore in plate rolling that the slab is first rolled to the required width, and is then turned through 90 degrees and rolled out to the finished thickness of the plate. The weight of the slab used is such that at the end of this operation the plate is of the required length. (Shearing allowance is of course made on length and width.) It will be seen therefore that plates are worked in two directions, the relative amount of length and cross work depending on the dimensions of the slab and the finished plate. A long narrow plate has received relatively little cross rolling, whereas a square plate may have received as much cross as length rolling. The effect of this on the mechanical properties will be referred to later.

Heavy forgings may be worked direct from the ingot, or the ingot may first be reduced to a bloom in the cogging mill. Small forgings, stampings, and pressings are manufactured from billets or plates, while small bars and sections are re-rolled from billets in a Merchant, Guide, or Rod Mill, provided with the necessary grooves or passes.

Rolling operations produce material which is uniform in section throughout its length, so that forging is necessary if a part of varying section is required. Of course, many such parts may be conveniently produced by machining from rolled material, but this practice is to be condemned for certain important parts of machinery where variations of section are considerable. The reason for this will be clear after we have considered the effect of hot work on the properties of steel.

The Effect of Hot Work on the Properties of Steel

It is common knowledge that the properties of the finished steel either in the "as rolled" or "as forged" condition are much superior to the properties of the same steel in the ingot state, and it is now necessary to discuss the reasons for this.

The effect of hot work is twofold. There is a refinement in the crystalline structure due to the breaking down of the coarse ingot crystals, and at the same time there are developed in the steel certain well-defined directional properties.

These two factors may be considered separately. First, with regard to the refinement of the crystalline structure, it has already been shown on p. 29, that when steel is heated beyond its critical range the austenite crystals which are formed commence to grow, also that the extent of this growth depends on the temperature and the time. The higher the



Fig. 41a.—Sulphide Inclusion, Unetched. $\times 350$

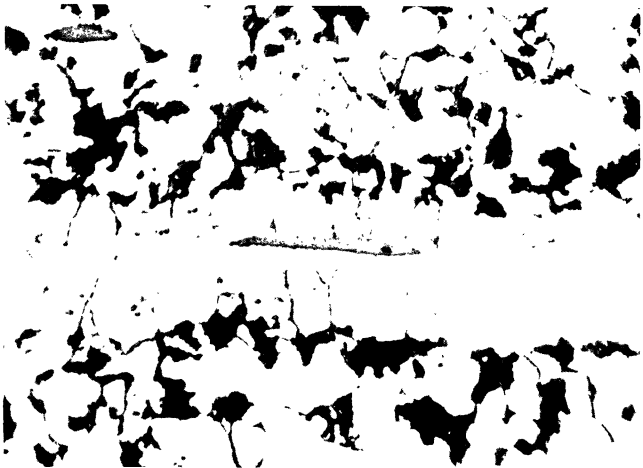


Fig. 41b.—Sulphide Inclusion in Ghost, Etched. $\times 350$

temperature and the longer the time at that temperature, the larger are the resulting crystals. The one condition necessary for crystal growth is freedom from external disturbance which will distort the metal. Now consider what happens when an ingot is forged or rolled. The heavy blows or pressure which cause a rapid change in the shape of the mass soon break down the large ingot crystals, and so long as this violent disturbance continues the growth of new crystals is prevented. As soon as work ceases, however, provided the temperature is high enough, crystal growth proceeds as the metal cools down undisturbed to the temperature of the critical range. Here the transformation occurs which leads to the formation of the normal structure of steel (pearlite with or without ferrite or cementite), and the larger the parent crystals of austenite the coarser is the final structure of the steel.

Finishing Temperature

The temperature at which hot work is stopped is known as the finishing temperature, and the above considerations show the importance of correct finishing temperature if the finest possible structure is desired in the steel, provided, of course, that the amount of work on the ingot has been sufficient to break up the original coarse crystals formed on solidification. To ensure this, specifications for large blooms or forgings usually provide that the cross-section of the ingot shall be reduced by at least 80 per cent. The best finishing temperature is just above the critical range. If work is continued below this range, the temperature becomes too low to relieve the induced strains, in other words, the metal is too cold to allow spontaneous recrystallization to take place and the structure is distorted. This is accompanied by an increase in the tensile strength and a corresponding decrease in the ductility of the metal. The lower the temperature below the critical range, and the greater the amount of work (as measured by the reduction in the cross-sectional area of the steel), the harder and more brittle does the metal become. As a general rule the thicker the section of the finished steel the higher will be the finishing temperature; consequently, the coarser the structure, and the lower the tensile strength, within limits. It is usual, therefore, to adjust the analysis of the steel accordingly. For example, a thick section will usually have a higher carbon content than a thin section where the same tensile properties are

desired. In figs. 43 and 44 (Plate 10), showing the "as rolled" structure of plates of different thickness made from the same cast of steel, the influence of finishing temperature is clearly illustrated. It will be understood that when the steel is subsequently heat-treated above the critical range, the effect of finishing temperature is eliminated.

The other aspect of hot work is its effect in developing directional properties in the finished steel. A similar feature was observed in wrought iron, in which the elongation of the slag globules in the direction of rolling was illustrated in

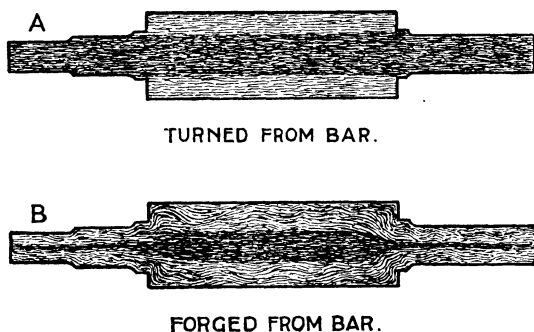


Fig. 45.—Flow Lines in Turned and Forged Shafts

fig. 22 *a*. Not only the slag, but every little area of local segregate becomes similarly elongated, thus imparting to the steel a fibre somewhat analogous to the fibre in wood.

The arrangement of these fibres in a rotor shaft, (A) machined from a rolled bar and (B) forged, is illustrated in fig. 45. This structure is revealed by a deep-etch test on the section (see Chap. XIII). From the nature of this structure, there is a tendency for the fibres to separate when a tensile stress is applied at right angles to them. It follows therefore that the fibres should always be arranged parallel to the tension stresses, or at right angles to the principal shearing or bending stresses as in the forged shaft (fig. 45 B). Besides the bad arrangement of the fibres in the shaft machined from the rolled bar there is another dangerous feature. In shaping the ends of the shaft, which are of comparatively small diameter, all the soundest portion of the steel is removed, leaving only the core of the

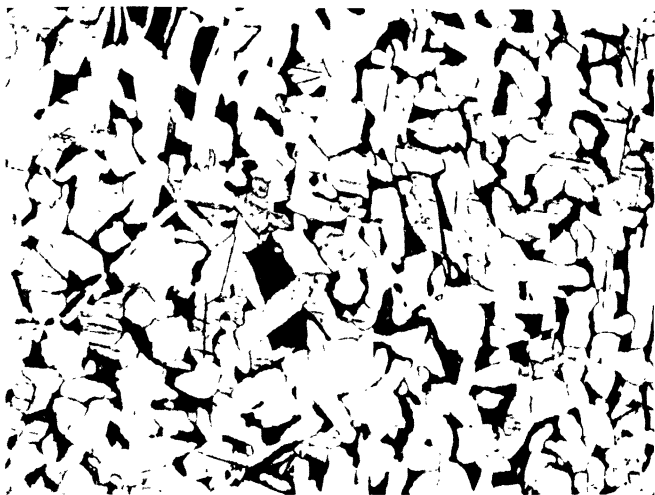


Fig. 43.— $1\frac{5}{16}$ in. Plate as Rolled ($C = \cdot 15$ per cent). $\times 100$

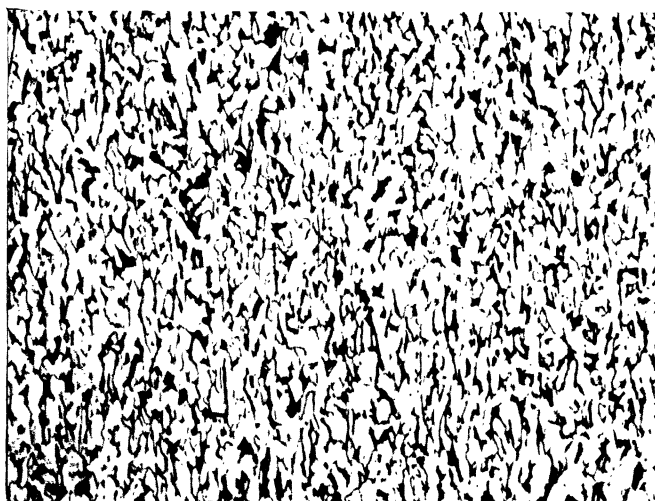


Fig. 44.— $\frac{5}{16}$ in. Plate as Rolled ($C = \cdot 15$ per cent). $\times 100$

original bar, in which segregated impurities are likely to be found. (Compare dark areas in figs. 45 A and B.)

The effect of hot work on the mechanical properties of steel is most marked in the ductility as measured by percentage elongation and reduction in area, and also in the notched bar toughness values. This is clearly illustrated in Table VI.

TABLE VI

EFFECT OF HOT WORKING ON MECHANICAL PROPERTIES OF STEEL
Carbon, .20 per cent; Manganese, .65 per cent; Silicon, .12 per cent.

Dimension of Plate or Bar.	Direction of Test.	Max. Stress. Tons/sq. in.	Elong. Per cent on 2 in.	Red. of Area. Per cent.	Izod Impact. Ft.-lbs.
Test piece as cast.		27.5	16	10	5
10' × 7' 6" × 1"	Length	30.0	35	55	40
	Cross	29.6	33	48	31
20' × 5' 0" × $\frac{5}{8}$ "	Length	31.0	32	50	45
	Cross	30.0	23	31	16
18' × 8" × 8"	Length	29.0	34	54	26
	Cross	28.2	26	28	18
18' × 5" dia.	Length	29.6	35	52	28
	Cross	28.3	20	24	12

CHAPTER VI

The Heat Treatment of Steel

The physical and chemical properties of steel are determined by its composition and structure. The composition of itself determines within limits what the structure will be, but we are here concerned primarily with changes in structure from other causes. For a given steel, any change in structure will result in a change in the properties, and conversely any change in properties can only occur as a result of a change in the structure. Structure is here used in the wider sense of "arrangement of the molecules of the material", whether or not a visible change in the crystalline formation takes place. Some of the structural changes are ultra-microscopic and can be detected only by X-ray analysis. Others have not yet been detected by any method, but most of those which have

important effects are revealed by microscopic examination.

The structure of a piece of steel and therefore its properties are changed by mechanical work or by heat treatment. Mechanical work, both hot and cold, is discussed elsewhere. By heat treatment is meant the operations of heating and cooling without mechanical work. The process comprises one or more of the following treatments, all of which are of the utmost importance, and require, therefore, the most careful consideration.

1. Normalizing.
2. Annealing.
3. Hardening.
4. Tempering.

The first three treatments depend for their effect on the constitutional changes which take place when steel is heated above its critical range. (The critical range is all temperatures between the lower and higher critical points Ac_1 , Ac_3 .) Recrystallization is followed by diffusion of the dissolved iron carbide until it is uniformly distributed through the austenite crystals. As already explained, the austenite crystals increase in size by absorbing adjacent crystals, as long as the temperature remains above the critical range. The rate of grain growth increases rapidly as the temperature is raised, and by excessive overheating the material may be burned. Burning results from heating steel to a temperature at which incipient fusion takes place at the grain boundaries. This permits of the penetration of oxygen from the atmosphere between the crystals, which thus become separated by a layer of brittle iron oxide. Fig. 46, Plate 11, shows a section cut from a burnt plate. The oxide film between the crystal grains is clearly visible in the unetched specimen.

Burnt steel cannot be restored to a serviceable condition and is fit only for remelting. Overheated material, if the burning stage is not reached, may be refined as described below. Unless otherwise stated the following remarks refer only to carbon and low alloy steels.

Normalizing

Heating to and, if necessary, holding at a suitable temperature above the transformation range, followed by cooling in a still atmosphere in order to refine the grain size, render the structure

PLATE II



Fig. 46.—Burnt Steel (Unetched).
× 55



Fig. 47.—24 per cent C Steel
as Cast. × 100



Fig. 48.—24 per cent C Steel
Normalized 900° C.; 3 hours.
× 100

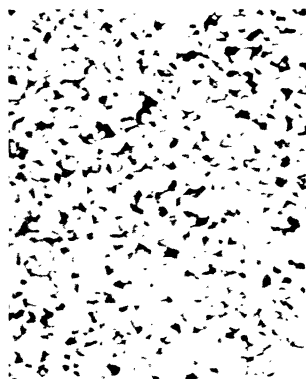


Fig. 49.—24 per cent C Steel
Normalized 950° C.; ½ hour. Re-
normalized 900° C.; ½ hour. × 100

more uniform, and also, as a rule, improve the mechanical properties.

It has already been shown that cast steel and hot worked steel which has been finished at a temperature well above the critical range will have a coarse structure. A typical structure of cast steel is shown in fig. 47, Plate 11. Material with such a structure is not satisfactory. The tensile properties and ductility are inferior, and an impact test would invariably show that the steel would offer but little resistance to shock, and would probably fail in service. Other things being equal, and within certain limits, the finer the grain size of the material, the better will be its tensile properties and the greater will be its resistance to dynamic stresses. The coarse structure which is illustrated in fig. 47 can be refined by normalizing as described above. The precise temperature and the time depend upon the coarseness of the structure to be refined and the thickness of the material. If the structure is very coarse, as in castings, a high temperature or prolonged soaking at a lower temperature is necessary to refine the grain. The best method, though more expensive and only employed in special circumstances, is a double normalizing: the first at a temperature of 950°C . and the second at 50°C . above the upper critical range. The structures obtained by a single and by a double treatment are illustrated in figs. 48 and 49. The correct normalizing temperature depends therefore to a large extent on the structure of the steel before heating, but for worked material it should not exceed the upper critical temperature by more than 50°C .

Full Annealing

Heating to and holding at some temperature above the transformation range followed by cooling slowly through the critical range.

The structure of annealed steel does not differ greatly from that of normalized steel, unless the annealing temperature has been high. When this occurs there is more time for grain growth as the material, cooling slowly, will remain a longer time above the critical range. The deposition of pearlite occurs more slowly in annealing and in consequence it will more closely approach the lamellar structure. The limit of proportionality, the yield point, and the tensile strength are reduced by annealing, while the impact value is also lower than

that of corresponding normalized steels. These differences are mainly due to the coarser grain of annealed material. Annealing then is carried out when refinement of structure and softening of the material are both required. Normalizing is of course more economical, as the heat and time losses in the furnace are considerably greater when annealing is adopted.

Sub-critical Annealing

Heating to and holding at some temperature below the transformation range followed by cooling at a suitable rate.

Forgings and other worked material, if finished at a temperature below the critical range of the steel, are in a strained or work-hardened condition, and are therefore somewhat brittle. This may be remedied by normalizing or full-annealing, or by sub-critical annealing (softening). Normalized steels if too hard for requirements may also be softened. This treatment consists in heating the steel to any desired temperature below the lower critical point (700°C.) and cooling in air or in the furnace. The temperature and time depend upon the degree of softening required, but below 550°C. no appreciable softening takes place.

Under normal conditions no change in structure results from sub-critical annealing, but if this treatment is prolonged at a temperature near the transformation range a structural change known as *spheroidizing* becomes evident, the carbide of the pearlite forming into small globules or spheroids. Apart from the greater softening thereby produced, a spheroidized structure, particularly when the carbon is high, renders steel much more easily machinable than when the structure is pearlitic. Cold working (q.v.) increases the rate of spheroidizing with sub-critical annealing.

Softening and spheroidization may also be produced by *isothermal annealing* (see p. 61). It may be remarked that none of the foregoing treatments produces any change in the density of the steel.

Hardening

Increasing the hardness by thermal treatment. This usually implies quenching from a temperature either within or above the transformation range.

As its name indicates, the iron-carbon equilibrium diagram (fig. 27) illustrates graphically the changes which take place when normal or equilibrium conditions are realized. This occurs when steel is normalized or annealed, but when it is cooled rapidly from a high temperature (that is, from above its critical range) there is not sufficient time for the transformation to take place at the equilibrium temperature, and the solid solution, austenite, persists to a lower temperature. When austenite breaks up at a low temperature, martensite is formed, and the steel is hardened. No hardening takes place unless the steel has been heated to a temperature at which austenite is formed.

Martensite (fig. 52, Plate 12) is a mixture of ferrite (alpha iron) and extremely finely divided cementite. The change from austenite to ferrite is accompanied by an increase in volume, and when this occurs at a low temperature the material is put in a condition of severe internal strain. This is the chief cause of the intense hardness of quenched steels.

The degree of hardness obtained by quenching steel depends upon three factors:

1. The composition of the steel.
2. The temperature to which it has been heated before quenching.
3. The rate at which it is cooled (i.e. the efficiency of the quenching medium).

With the physico-chemical causes of hardness we are not further concerned. It will be sufficient to show that hardening is due to carbon, and that, up to a certain maximum value, the greater the carbon content, the harder will be the quenched steel. Pure iron, if it could be obtained, would not be hardened by quenching, however drastic, from any temperature. As already stated, even commercial wrought iron and ingot iron of a high degree of purity are only slightly hardened by such treatment. The effect of increasing the carbon content is shown in Table VII. It will be observed that the maximum hardness is obtained with a carbon content of about .7 per cent.

The reason for this is that with a higher carbon content drastic quenching results in some of the austenite remaining untransformed, so that the maximum hardness is not obtained.

TABLE VII

THE HARDNESS OF QUENCHED CARBON STEELS

Carbon. Per cent.	Quenching Temperature, Degrees C.	Brinell Hardness.
·12	910	161
·20	900	320
·35	870	550
·50	840	675
·70	800	713
·90	750	683
1·18	800	683

Alloy steels are discussed later, but it may be mentioned here that the effect of additional elements on a carbon steel is to render the solid solution more stable. That is to say, the changes on cooling occur at a lower temperature, and by quenching are easily depressed to such a temperature as will result in hardening. Thus alloy steels are in general hardened by a much less drastic quenching than is necessary for plain carbon steels. Indeed by means of alloying elements, steels can be produced which are hardened in the same way as plain carbon steels are normalized. These comprise what are known as the "air-hardening steels".

Although the majority of alloy steels contain a comparatively small proportion of carbon, the hardening is primarily due to that element. Alloys of iron and other metals in the absence of carbon cannot be obtained with a hardness approaching that of a water-quenched carbon steel. Nor are alloy steels themselves as hard as plain carbon steels when quenched. Their advantages are that they are more easily hardened and consequently the mechanical properties in the quenched and tempered condition are superior.

Tempering

Re-heating hardened, normalized, or mechanically worked steel to some temperature below the transformation range and if necessary holding at that temperature, followed by cooling at a suitable rate.

As has already been stated, quenched steels are in a state of severe strain. They are consequently exceedingly brittle and entirely unsuitable for engineering purposes. Tempering is the reheating process by which quenched steels are rendered fit for service. The purpose and effect of reheating quenched

steel is to remove the hardening strains and to soften and toughen the steel to the desired extent. As the tempering temperature is raised, the hardness and tensile strength are progressively lowered, while there is a corresponding increase in the elongation and reduction of area (fig. 50). The impact value, however, is not appreciably improved until the tempering temperature approaches 500° C. The removal of strains by tempering is accompanied by a gradual increase

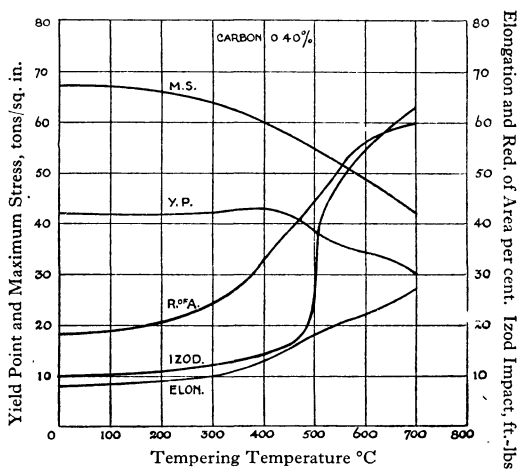


Fig. 50.—The Effect of Tempering on the Mechanical Properties of Quenched Carbon Steel

in the density of the steel, and when all strains are removed the density becomes the same as that of the material in the annealed condition. The above described changes are illustrated in figs. 50 to 54, and Table VIII. In the higher carbon steels the acicular structure of martensite is most pronounced. The martensite tends to form along cleavage planes in the austenite crystals. The white constituent in fig. 56 is austenite which has been retained by quenching. In carbon steels austenite is partially retained when the quenching is very drastic and the carbon content over .7 per cent. Reheating carbon steels to 300° C. (fig. 57) results in a slight tempering of the martensite and the remaining austenite is transformed on cool-

ing (see p. 94). It will be noted (fig. 54) that tempered martensite has a spheroidized structure. Certain alloy steels, on the other hand, on quenching from a high temperature show a structure entirely austenitic, which is transformed to martensite not by reheating but by cooling to a much lower temperature. This means that, by quenching, the critical transformation has been depressed to a point below the normal atmospheric temperature. The structure of austenite is illustrated in fig. 58. It is of interest to note here that steels which consist entirely of austenite are non-magnetic (see pp. 27 and 96).

TABLE VIII

THE MECHANICAL PROPERTIES OF QUENCHED AND
TEMPERED STEEL

Carbon, .4 per cent; Manganese, .7 per cent; Silicon, .21 per cent.
Water-quenched, 850° C.

Tempering Temperature. Degrees C.	Yield Point. Tons/sq. in.	Max. Stress. Tons/sq. in.	Elong. Per cent on 2 in.	Red. of Area. Per cent.	Impact. Ft.-lbs.	Density. Grams per c.c.
As rolled ..	20	40	25	47	12	7.840
As quenched	42	67	8	18	10	7.796
300 ..	42	64	10	24	12	7.802
400 ..	43	60	13	33	14	7.816
500 ..	39	55	18	44	28	7.824
600 ..	34	48	22	56	55	7.832
700 ..	30	42	27	60	63	7.840
Normalized at 850° C. ..	26	41	30	53	45	7.840

Steels which have been reheated (tempered) after quenching may be cooled in air, oil, or water. It is found that in some alloy steels the rate of cooling from the tempering temperature has a pronounced effect on the impact properties. Such steels are subject to what is known as "temper brittleness". If cooled after tempering at a rate slower than a certain critical rate, they are brittle under the Izod impact test. It is therefore essential that such steels be cooled in water or oil from the tempering temperature, if satisfactory results are to be obtained. Table IX shows the effect of various cooling rates on the mechanical properties of a nickel-chrome steel, and discloses that the phenomenon of temper brittleness cannot be discovered by any ordinary test other than an impact test. A small amount (0.25 per cent) of molybdenum added to steels



Fig. 51.—40 per cent C Steel as Rolled. $\times 300$



Fig. 52.—40 per cent C Steel W.O. 850° C. $\times 350$



Fig. 53.—40 per cent C Steel W.O. 850° C., and Tempered at 300° C. $\times 350$

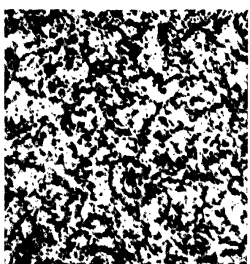


Fig. 54.—40 per cent C Steel W.O. 850° C., and Tempered at 600° C. $\times 350$



Fig. 55.—40 per cent C Steel Normalized 850° C. $\times 300$



Fig. 56.—1.0 per cent C Steel W.O. 1100° C. $\times 350$



Fig. 57.—1.0 per cent C Steel W.O. 1100° C., $\times 350$



Fig. 58.—Austenite in 3 per cent Ni-Cr Steel W.O. 1000° C. $\times 250$

otherwise susceptible to temper brittleness is usually sufficient to render them immune.

From the foregoing remarks it is apparent that hardening strains, density, tensile strength, and ductility are all closely related to each other, so that a change in any one of these will be accompanied by a change in the others. The impact value, however, is not so closely related to the other properties, and, as this property may be of great practical importance, an explanation of this divergence is necessary. We have seen that the grain size has a pronounced effect on the impact value, but since the tempering treatment in no way affects grain size, the explanation must be sought elsewhere. In p. 34 it was pointed out that iron sulphide in steel forms a film round the

TABLE IX
THE MECHANICAL PROPERTIES OF NICKEL-CHROME STEEL
OIL-HARDENED AND TEMPERED AT 630° C.

Method of Cooling from Tempering Temperature.	Limit of Proportion- ality. Tons per sq. in.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elong. Per cent. on 2 in.	Red. of Area. Per cent.	Impact. Ft.-lbs.
In furnace ..	29	38.4	50.0	24	68	9
In air ..	31	40.0	49.8	25	64	25
In water ..	29	39.2	49.8	23	63	56

grain boundaries, and that in consequence of this film, steel containing this inclusion is brittle. If in hardened steels there is a film of some substance round the grain boundary, its presence will explain the brittleness of such steels. On this theory, the film formed on hardening is not redissolved on tempering until a temperature of 500° C. is reached. The solution of this film at this temperature removes the brittleness. This theory may also be applied to explain the phenomenon of temper brittleness. In steels which possess this property the film dissolved at a temperature of 500° C. or higher is reprecipitated at the grain boundary on cooling, and the brittleness remains. This reprecipitation may, however, be suppressed by quenching, by which means the re-formation of the film round the grain boundary is prevented, and the impact value of the steel consequently raised. The foregoing explanation is generally accepted as true, but the actual constitution of the film is a matter of controversy, with which we are not concerned. It is sufficient to note that the quantity of this constituent need

only be very small. This is illustrated by the fact that gold, the most malleable and ductile of metals, becomes, by the addition of only .05 per cent bismuth, so brittle that it may easily be ground to a powder of single crystals. The bismuth forms a thin film round the gold crystals, which are thus easily disintegrated.

The film in brittle steels has not been detected by microscopic examination, but X-rays may yet be employed to detect it. It is believed to be a carbide of iron.¹

Reference has been made above to pearlite, austenite, and martensite. Brief mention must now be made of *troostite* and *sorbite*. Unfortunately, these terms have been applied indiscriminately to structures obtained by tempering quenched steels and to those obtained by partial quenching only. In the opinion of the authors, they should be applied only to steels in the latter condition. Troostite and sorbite are illustrated in figs. 59 and 60 (Plate 13). Until recently troostite and sorbite were thought to be finely divided mixtures of ferrite and cementite, troostite being more of the nature of an emulsion. The invention of the electron microscope enabled magnifications up to 100,000 diameters to be obtained, and it has been shown that the structure of troostite and of sorbite is exactly the same as that of pearlite, but in a very much finer form. Troostite occurs only in carbon steels, and is formed when the rate of cooling has not been sufficiently rapid to result in complete hardening. Thus troostite is associated with martensite. Sorbite is formed at slower rates of cooling. Troostite and sorbite are somewhat harder than pearlite, but this increased hardness is due solely to the fine state of division of the constituents. The density of troostite and that of sorbite is the same as that of pearlite, indicating that these are not strain-hardened. The structure of normalized steels is frequently described as sorbitic pearlite to distinguish it from the coarser pearlite obtained by prolonged annealing.

It should be noted that tempering refers to the reheating of quenched steels only when the temperature does not exceed the critical range of the steel. Heating beyond this range will completely undo the effect of quenching and will produce a normalized steel on cooling in air.

¹ *Journal of the Iron and Steel Institute*, 1926, 11, p. 359.

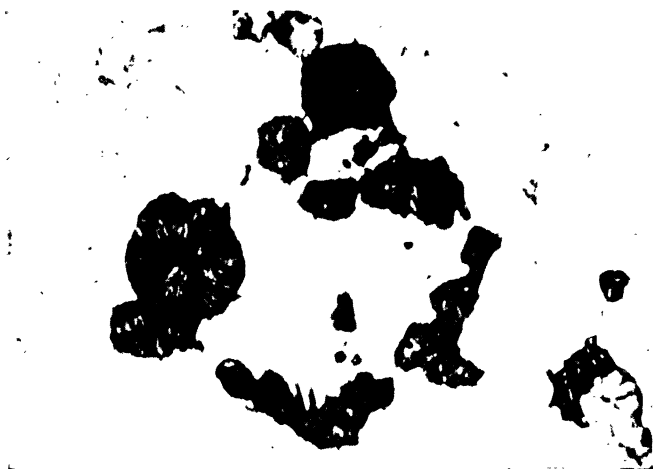


Fig 59.—Troostite (Dark Constituent). 460

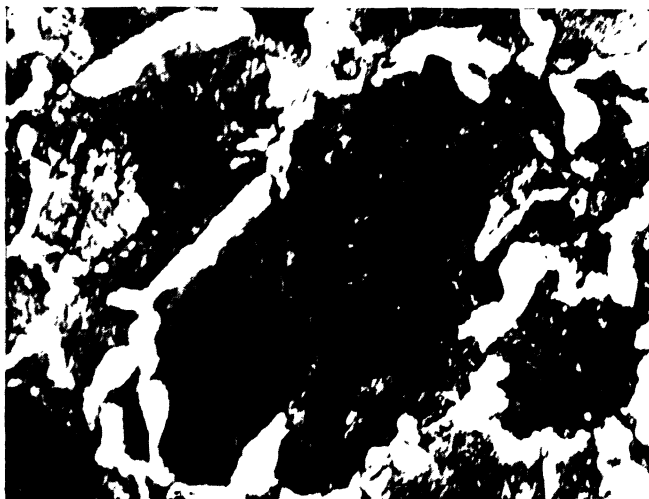


Fig. 60.—Sorbite (Dark Constituent). $\times 460$

Precipitation Hardening

Just below the A_{c1} point (700° C.) ferrite is capable of dissolving $\cdot 035$ per cent of carbon, which, on slow cooling, is precipitated. If, however, the steel is quenched from the temperature of maximum solubility of carbon, the carbon is retained in solution and is precipitated slowly with the passing of time or more quickly by reheating up to 100° C. This precipitation at low temperatures results in hardening of the steel, the phenomenon being known as *precipitation hardening* or *quench ageing*.

The following is an example of precipitation hardening in basic open hearth mild steel.¹ The analysis of the material was:

C per cent.	Si per cent.	S per cent.	P per cent.	Mn per cent.	Cr per cent.
$\cdot 10$	$\cdot 083$	$\cdot 033$	$\cdot 017$	$\cdot 41$	Nil

Small samples were quenched from 680° C. and hardness tests taken after 6 hours (B.H. 143), and 50 days (B.H. 189). The increase in hardness, amounting to 32 per cent, is also accompanied by a low resistance to impact, the Izod value being from 10 to 20 ft.-lb.

The hardening effect is attributed to the strain produced in the ferrite by precipitation at low temperatures, so that the maximum precipitation hardening is obtained with a steel containing $\cdot 035$ per cent of carbon. With a higher carbon content there is less free ferrite and, therefore, less hardening, so that this phenomenon is negligible in medium and high carbon steels.

Mass Effects in Heat Treatment

The temperatures at which the critical changes take place when a piece of steel is heated are independent of the rate of heating. The centre of a large mass of steel which has been heated above the critical range has practically the same structure as the outer portion, provided that during the soaking stage the latter has not been overheated. The rate of cooling, however, has been shown to have a most important bearing on the structure and properties of the material. The outer layers of a large mass of steel will cool at a greater rate than

¹ *Iron and Steel Institute*, 1938, No. II, p. 246.

the centre, which can only lose heat to the outer layers. In normalizing or annealing this does not matter, for no portion of the mass cools quickly enough to depress the critical points below the ordinary temperature of these changes. But it is possible to quench a piece of steel so that part of the material is cooled quickly enough to result in hardening while the remainder cools at such a rate that the critical changes occur at the normal temperature, and hardening does not take place. In general, carbon steels require to be cooled in cold water in order that hardening may be complete. But a $\frac{1}{2}$ -in. dia. bar of steel containing say .8 per cent carbon would be satisfactorily hardened by cooling in oil. On the other hand, the centre of a 3-in. dia. bar of the same composition could not be hardened satisfactorily by the most drastic quenching. (See Table X.)

TABLE X

THE EFFECT OF MASS ON THE HARDENING OF A STEEL
CONTAINING .8 PER CENT CARBON

Dia. of Bar. Inches.	Heat Treatment.	Position of Test.	Brinell Hardness.
0.5	Oil-quenched—850° C.	Centre.	555
		Outside edge.	555
3.0	Water-quenched—850° C.	One inch from centre.	363
		Centre.	302

The mass effect is simply one aspect of the time effect, or in other words, the effect of the rate of cooling, for a proper appreciation of which reference must be made to isothermal transformation (or S) curves (fig. 61.) The preparation of these S curves is a slow process involving a great deal of experimental work. Briefly, test specimens are soaked at a temperature above the Ac range for a sufficient time to produce a uniform austenitic structure, and rapidly cooled in metal baths at various temperatures at which they are held for various times. They are then quenched in cold water and examined microscopically. That portion of the steel which is not transformed at the holding temperature and time will have a martensitic structure as a result of the subsequent quenching. Another method is to incorporate the specimen in a dilatometer which is transferred to the metal bath. The progress of the reaction can then be observed since the trans-

formation is accompanied by an increase in length of the specimen.

Fig. 61 shows the S curves of a .9 per cent carbon steel, and a few examples will suffice to explain their significance. If a sample of the steel is cooled to 700° C. and held at that temperature for one hour, the transformation will be completed and, no matter how fast the material is cooled thereafter, the structure will be pearlitic and the material will be soft. This is an example of *isothermal annealing*.

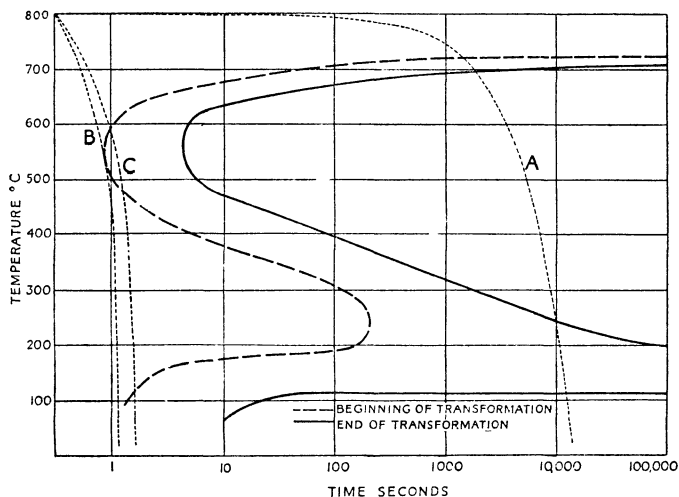


Fig. 61.—S Curves for .9 per cent Carbon Steel

Superimposed on the S curves are curves showing different rates of continuous cooling. For example, Curve A represents the cooling rate of a bar fully annealed, and shows that the transformation will be complete by the time the material has reached a temperature of 700° C. The critical cooling rate (Curve B) is that which will just miss the nose of the S curve, so that no transformation will take place until 80° C., at which temperature martensite is formed.

With a continuous rate of cooling below the critical cooling rate (Curve C), partial transformation may take place between 590° C. and 480° C., with the formation of some sorbite. It

will be noted that between 480°C. and 120°C. no change occurs on continuous cooling, so that no intermediate products are formed. The transformation is completed below 120°C. , at which temperature martensite is produced. Thus, with increasing rates of continuous cooling the resulting products will be Pearlite — Sorbite — Sorbite and Troostite — Troostite and Martensite — Martensite. The hardness thus depends on the extent to which the transformation has

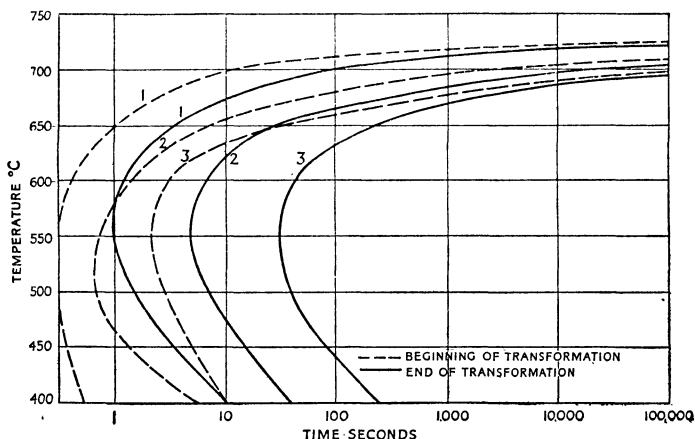


Fig. 62.—Effect of Manganese on S Curves

C per cent. Mn per cent.

(1)	.59	.30
(2)	.50	.91
(3)	.65	1.32

taken place at the higher temperatures and at the lower.

With lower or higher carbon the S curves are displaced to the left, so that the critical cooling rate for these steels is faster. A slower critical cooling rate than can be obtained with a carbon steel is necessary to harden thoroughly a bar of diameter greater than $\frac{3}{4}$ in. It is for this reason that alloy structural steels have been developed. The effect of various alloying elements can be studied by an examination of the S curves. For example, fig. 62 shows the effect of increasing manganese on the S curves, which are displaced to the right. The critical cooling rate is therefore slower. Thus manganese has the effect of considerably increasing the response of

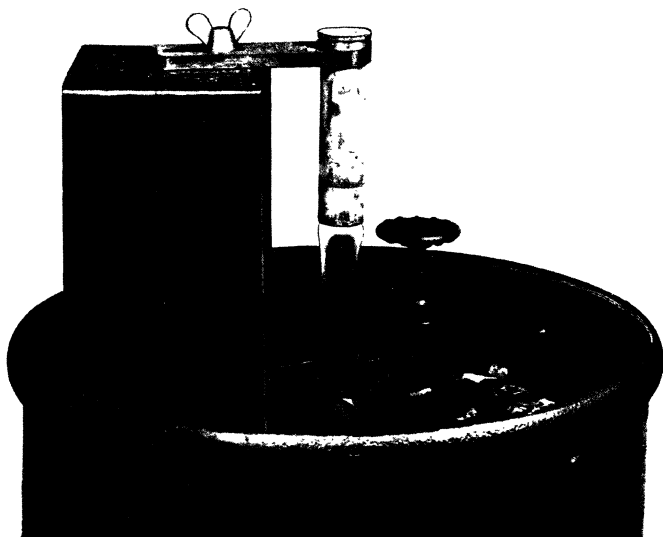


Fig. 64.—Jominy End-quench Test

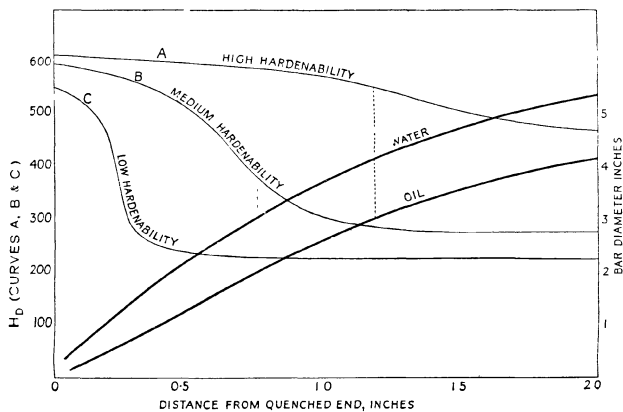


Fig. 65.—Hardenability Curves. (See Text)

steel to depth hardening. Nickel has a similar, though less pronounced, effect. Chromium also displaces the S curves to the right, but, as can be seen from fig. 63, chromium steels transform more rapidly in the region of 400°C . This intermediate transformation is known as the Ar'' point. Thus it is possible to quench chromium steels in such a way as to suppress the Ar_1 transformation, but if the rate of cooling is not

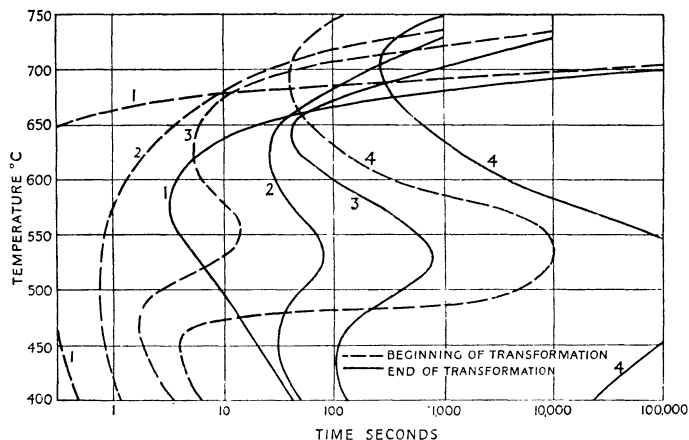


Fig. 63.—Effect of Chromium on S Curves

	C per cent.	Mn per cent.	Cr per cent.
(1)	·35	·37	·0
(2)	·37	·37	·57
(3)	·42	·68	·93
(4)	·32	·45	1·97

sufficiently fast the intermediate transformation may take place. The product of this transformation (Bainite) resembles martensite in appearance, but tempered Bainite has mechanical properties inferior to those of tempered martensite. The effect of molybdenum is similar to that of chromium, but molybdenum is much more powerful and is rarely used in proportions greater than 0·5 per cent. Vanadium is a very powerful hardener, its effect being similar to that of manganese, but vanadium is used only in very small proportions.

The effect of alloying elements is discussed further in Chap. VIII.

Effect of Grain Size

It has been shown that heating the steel beyond the critical range results in "grain growth", i.e. the grains increase in size and the structure becomes coarser. Increasing the grain size lowers the critical cooling rate in the same way as do alloy additions. This effect is most marked in carbon steels and is slight in alloy steels, nor has the grain size any influence on the intermediate (Ar'') transformation.

Hardenability

In selecting a steel for a particular purpose the engineer is primarily concerned with its mechanical properties. If these can be obtained from a steel in the normalized or annealed condition the response to quenching is of no importance, but if a heat-treated steel is required it is necessary to know to what depth the material is capable of being hardened. This property is known as the *hardenability*. Hardenability should not be confused with hardness, for it is not related to the maximum hardness obtainable on quenching. This is a function of the carbon content, and is not affected appreciably by alloy additions. On the other hand, carbon steels have a low hardenability no matter how high the carbon content, whereas alloy steels with a low carbon content may have a high hardenability.

The most useful test for indicating the hardenability of a steel is known as the Jominy End-quench Test. The test piece, 1 in. dia. and 4 in. long, is heated in a furnace to the required temperature for a definite time. The test piece is then transferred to a fixture and a jet of water is directed against one end of the test piece (fig. 64). The conditions are standardized throughout, although minor variations make no appreciable difference to the test. Thus the Jominy test piece is quenched with various cooling rates throughout the length of the test. The test piece then has two flats ground on two positions, 180° apart. Hardness determinations are made along these flats and the Jominy curve plotted as illustrated in fig. 65, Plate 14.

Visual examination of the Jominy curve is sufficient to give a qualitative estimate of the hardenability. A quantitative determination of the extent to which a section of steel will harden depends on a correlation between the cooling condi-

tions at any position in the section, and the cooling conditions at a definite position on the Jominy test. By accurate experimental work, Jominy determined the cooling rate at 705°C. at different distances from the quenched end of the test piece, and similarly he determined the cooling rate at the centre of various diameters of bars quenched in oil and in water. By this means, curves may be drawn to show the diameter of bar which will have the same cooling rate at the centre as a given point on the Jominy curve, and therefrom, the hardening of a bar of steel under known quenching conditions can be calculated. The curves for oil and water are shown in fig. 65. Two examples will suffice to illustrate the use of these curves in conjunction with the Jominy test.

For the steel whose Jominy curve is A the rate of cooling at the centre of a 3-in. dia. bar quenched in oil is the same as that of a point on the Jominy test piece 1.2 in. from the end. The H_D at the centre of the bar will, therefore, be 550. Similarly, for the steel whose Jominy curve is B the centre of a 3-in. dia. bar quenched in water will have an H_D of 375. This and other methods of correlating the cooling condition are not exact. The above method can only be applied to steels of medium hardenability.

For a given steel the greater the hardness in the "as quenched" condition the higher will be the yield point and the impact values on tempering to any given tensile strength. The elongation and reduction of area are not so dependent on the "as quenched" hardness. The minimum "as quenched" hardness required to give satisfactory mechanical properties on quenching and tempering to a given tensile strength depends upon the composition of the steel, and can be determined only by practical experience. It may be said, however, that in general lower carbon steels do not require the same quenched hardness as do higher carbon steels of the same type (see also p. 84).

Determination of Critical Range

It is, of course, obvious that neither the S curves nor the Jominy curves give any indication of the initial temperature necessary before hardening. This must be determined for each particular type of steel, and is shown by an ordinary heating curve or by a dilatometer test. A simple but useful

workshop instrument known as the Gale dilatometer is illustrated in fig. 66.

The test piece, 2 in. long, is placed at the closed end of the silica tube, and slowly heated in an electric furnace. Any movement of the free end of the test piece is transmitted by another silica tube to a dial gauge graduated in 0.0001 in. The spindle of the dial gauge is fixed by a set-screw to a cylindrical invar block which rests on the upper end of the inner

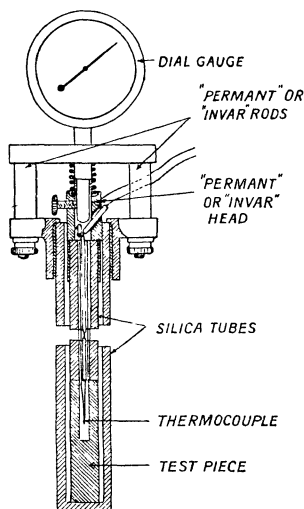


Fig. 66

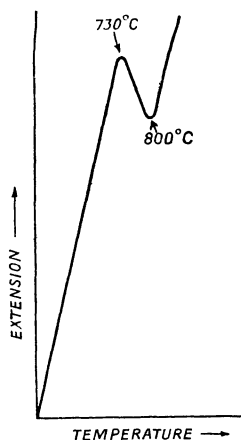


Fig. 67

silica tube, close contact between the test piece, silica tubes, and invar block being maintained by a helical spring. The dial gauge is carried on a crossbar mounted on two invar pillars which are attached by means of removable nuts to a brass collar in which the outer silica tube is mounted. A thermocouple to measure the temperature of the test piece is placed in a hole in the test piece, the ends being connected to a millivoltmeter.

By plotting simultaneous readings of temperature and change in length the critical range can be determined, since during this there is first of all a contraction and then an expansion, as illustrated in fig. 67.

The temperature of quenching is usually about 50° C. above the critical range.

Quenching Cracks

When a bar of steel is quenched, thermal contraction proceeds in the normal way till at the surface the temperature has reached the change point, when a sudden expansion takes place. At the same time the interior of the bar is still contracting thermally. The stresses thus set up may be sufficient to cause quenching cracks, and the more drastic the quenching the greater will be the stresses and consequently the greater will be the danger of cracking. Such cracks do not necessarily occur immediately on quenching, but may take place several hours later. Thus tempering should follow the quenching operation as soon as possible.

Heat-treatment Operations

Every stage of the heat treatment operation requires the utmost care, especially with high-carbon and high-alloy steels. The following items summarize the precautions necessary:

1. Do not charge cold material of large section into a hot furnace.
2. Heat slowly and uniformly.
3. Soak 30 min. for each inch of cross-section, avoiding overheating.
4. Avoid excessive scaling, for heavy scale reduces the efficiency of quenching and results in soft spots.
5. Dip the job in the quenching bath with the major axis vertical, to avoid distortion.
6. In water quenching, agitate the bath or the job, to prevent bubbles of steam adhering to the surface and causing soft spots.
7. Temper as soon as possible after quenching.

The Relation of Design to Heat Treatment

Reference has been made to the necessity of special care in the heat-treating of steel articles which have parts of different section. Unequal cooling in quenching such articles is unavoidable and internal strains are set up. These may result in distortion or cracking of the steel, and certainly will reduce

its reliability in service. The extent to which internal strains are developed depends on two factors, the quenching rate, and the design of the article. The heat-treater can choose the one, the engineer is responsible for the other, and not infre-

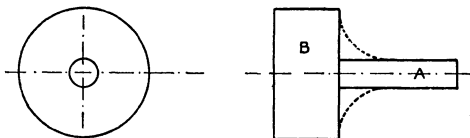


Fig. 68

quently his design has put too severe a strain on the resources of the heat-treatment department. For example, a piece of steel of the design shown in fig. 68 would almost certainly crack on quenching at the junction of the light and heavy

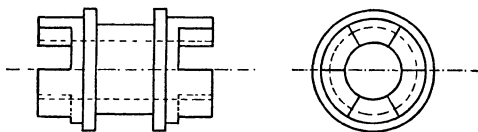


Fig. 69.—Double-ended Claw Clutch

Bad design for heat treatment. Variation of thickness, sharp corners. Should have fillets in all corners, and as uniform cross-section as possible.

sections. The part "A" would harden and therefore expand long before "B" reached the transformation temperature. A job of this nature is best made of two parts which could be separately treated and then screwed or keyed together. If this

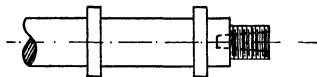
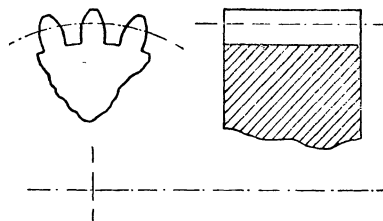


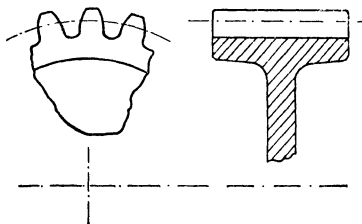
Fig. 70.—Mandril of bad design for heat treatment.
Thin collars, sharp corners

is impracticable, a generous fillet should be provided as shown by the dotted line. By this means, the internal strains would be distributed as evenly as possible and the danger of cracking reduced to a minimum. Examples of good and bad designs

from a heat-treatment point of view are illustrated in figs. 69 to 71. It is hoped that these will indicate to the engineer how



A. Long teeth, sharp roots. Small section teeth on solid body of wheel. Serious danger of cracks at roots of teeth



B. Shorter teeth, good fillets at roots and where web joins rim. Solid metal cut away under rim to make cross-section of uniform mass

Fig. 71

he may lighten the task of the heat-treater, and in so doing reduce his own troubles when the material is put into service.

CHAPTER VII

Plain Carbon Steels

Having discussed the effect of carbon on the structure and properties of iron, and also the fundamental principles of heat treatment, we may now proceed to examine more fully the composition, heat treatment, and mechanical properties of the principal carbon steels.

There is no well-defined line of demarcation between carbon

steels and alloy steels, but generally carbon steels comprise those alloys which contain not more than 1·0 per cent manganese, 0·3 per cent silicon, and negligible proportions of other alloying elements.

The steels described are either acid or basic open-hearth steels, which include almost all the plain carbon steels used in engineering. Crucible and electric furnace steels are employed in the manufacture of special castings, tool steels, and high-grade alloy steels, while acid Bessemer steels are sometimes utilized in structural work, such as buildings and bridges, and for rails. Basic steel may have a slightly lower tensile strength than acid steel of the same composition, but the difference is of little or no practical importance.

It will easily be understood that steel cannot be made to an exact analysis, and that, in consequence, specifications must set higher and lower limits to the percentages of the various elements required or permitted. Impurities such as phosphorus and sulphur are limited by specifying a maximum permissible content, usually 0·05 per cent or 0·06 per cent of either. The carbon content can be controlled within a range of from $\pm 0\cdot02$ per cent in low carbon steels to $\pm 0\cdot05$ per cent in the higher carbon steels, while the manganese and silicon contents may be specified within a range of $\pm 0\cdot05$ per cent. Not many engineering specifications set limits to the analysis of the material, with the exception of the sulphur and phosphorus contents. Instead, the tensile strength is specified with a range of from four to six tons per square inch. Thus the manufacturer may vary the carbon, silicon, and manganese contents within the above-mentioned limits. The effect of silicon and manganese on the tensile strength has already been discussed. The silicon content in plain carbon steels usually varies between 0·03 per cent and 0·15 per cent, and within these limits has no pronounced effect on the mechanical properties. The manganese content, however, is of more importance. As already stated manganese raises the limit of proportionality, the yield point, and the Izod impact value without detriment to the other qualities of the steel. For a given tensile strength, then, a steel with a high manganese content is superior to one with a low proportion of that element. The beneficial effect of manganese is evident even in steels "as rolled", but is more pronounced in normalized and heat-treated material.

In the following pages the carbon steels are described in the order of increasing carbon content, small arbitrary limits of carbon being grouped together as a class. The mechanical properties in the rolled and normalized or heat-treated conditions are discussed, and reference is made to the appropriate British Standard Specification (B.S.S.). Finally, the class of work for which the various steels are suitable is indicated. Although few specifications require the measurement of the yield point, reduction of area, or impact values, these are included for information.

Unless otherwise stated the phosphorus and sulphur contents are .05 per cent maximum. Test results of heat-treated material refer to bars of $1\frac{1}{8}$ in. dia. at the time of treating.

Elongations were measured on British Standard Test Pieces. Impact tests were taken on the standard Izod 120 ft.-lb. machine.

Group 1.—Dead Soft Mild Steel.

Carbon.	Manganese.
Per cent.	Per cent.
.12 max.	.3/5

Mechanical Properties

	Yield Point.	Max. Stress.	Elong.	Reduction	Impact.
	Tons	Tons	Per cent	of Area.	Ft.-lbs.
	per sq. in.	per sq. in.	on 8 in.	Per cent.	
As rolled or normalized, 900° C. }	12/15	22/25	30/35	55/65	50/80
Quenched in oil or water, 900° C. }	16/20	26/32	25/30	60/65	80/100

These steels are usually supplied in the "as rolled" condition. The finishing temperature in the rolling mills is never likely to be high enough to produce a coarse structure, as the upper critical point occurs at a temperature of about 880° C. Similarly, the lower limit of rolling temperature is seldom such as results in appreciable hardening of low carbon steels. For these reasons the mechanical properties of plates and bars as rolled are usually as good as those of normalized material.

As is indicated by the high elongation and reduction of area, these steels are very malleable and ductile, and therefore withstand considerable cold work such as flanging, pressing, and stamping. Accordingly, they are used in sheet form for

the manufacture of deep pressings, and for welded or solid-drawn tubes. The welding qualities are almost as good as those of the highest grade of iron.

For bolts, studs, and similar articles which require to be machined, small bars may be quenched in oil or water. The improvement in the mechanical properties brought about by this treatment is shown above. In addition, quenching improves the machining properties, eliminating the tendency to tear when being threaded or broached. Tempering after quenching is not necessary, internal strains arising from this treatment being negligible. This is evident from the high impact value obtained in the quenched condition.

Group 2.—Mild Steel.

Carbon. Per cent.	Manganese. Per cent.
·10/·16	·4/·6

Mechanical Properties.

	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elong. Per cent on 8 in.	Red. of Area. Per cent.	Impact. Ft.-lbs.
As rolled or normalized, 900° C. }	13/16	23/28	27/31	50/60	40/70
Quenched in oil or water, 900° C. }	18/24	30/36	22/27	50/60	50/90

The properties of these steels are similar to those of Group 1. The higher tensile strength is accompanied by a corresponding reduction in the ductility and toughness, which are, however, still very high. With normal sulphur and phosphorus contents, these materials are used for plates and bars for welding and cold working. With sulphur and phosphorus contents specified ·03 per cent max., these steels are widely employed as an economical substitute for copper in the manufacture of fire-box plates for locomotives (B.S. 16). As with the softer grades of steel, small bars of this group may be quenched in oil or water without tempering.

Group 3.—Mild Steel.

Carbon. Per cent.	Manganese Per cent.
·15/·25	·4/·9

By far the greatest quantity of plates, bars, and sections used in shipbuilding, boiler manufacture, constructional work, and

general engineering are included in this group. The tensile strength varies from 26 to 33 tons per square inch, the other properties depending upon the size of plate or section. The steels are commonly supplied "as rolled", but very thin sections may require annealing or softening, while heavy plates are usually normalized, as also are bars for which a high impact value is specified. The requirements of Lloyds, British Corporation, and other surveys and of the B.S.I. for structural steels for boilers, ships, railways, bridges, and building construction are met by the material in this group.

The following analyses and test results are typical of the series, and are compared with the requirements of the appropriate specifications.

Boiler Shell Plate $1\frac{1}{2}$ in. thick. Normalized 880° C.

	Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
	·24	·65	·04	·042	·034	
	Max. Stress. Tons/sq. in.	Elongation. Per cent on 8 in.		Reduction of Area. Per cent.		Impact. Ft.-lbs.
Length	31·4	24		49·0		35
Cross	30·8	23		44·0		25
B.S.S. 14	28/32	20 min.		—		—

Corrugated Furnace Plate, $\frac{5}{8}$ in. thick—as rolled

	Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
	·18	·62	·03	·04	·036	
	Max. Stress. Tons per sq. in.	Elongation. Per cent on 8 in.		Reduction of Area. Per cent.		Impact. Ft.-lbs.
Length	29·2	26·0		52·0		41
Cross	28·6	24·0		41·0		24
B.S.S. 14	26/30	23·0		—		—

3 in. × 3 in. × $\frac{5}{16}$ in. angle

	Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
	·20	·55	·02	·042	·036	
	Max. Stress. Tons per sq. in.		Elongation. Per cent on 8 in.		Reduction of Area. Per cent.	
As rolled	33·1		18·0		32·0	
Softened, 630° C.	29·4		26·0		45·0	
B.S.S. 24, Part 6	28/33		20·0 min.		—	

High Elastic Limit Steel

Within recent years the importance and value of heat treatment in structural steels have received prominence by the introduction of "high elastic limit steels" for shipbuilding purposes. Where such steels are employed, Lloyds and British Corporation surveys permit of a substantial reduction in the scantlings of ships under their classification.

One such grade of steel known as "Martinel Steel" is specified to have the following mechanical properties in the normalized condition:

Limit of Proportionality. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation. Per cent on 8 in.
15 min.	29/34	20 min.

The composition of the steel used is approximately:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.
·24	·76	·10

The mechanical properties of a $\frac{3}{4}$ -in. thick plate in the "as rolled" condition are as follows:

	Limit of Proportionality. Tons per sq. in.	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elongation. Per cent on 8 in.
Length	9·5	16·0	31·8	25·0
Cross	9·2	15·8	31·4	21·0

The properties of the same plate after normalizing at various temperatures are shown in Table XI, and the corresponding micro-structures are illustrated in figs. 72 to 74, Plate 15.

TABLE XI

MECHANICAL PROPERTIES OF MARTINEL STEEL AFTER NORMALIZING AT VARIOUS TEMPERATURES

Normalizing Temper- ature.	Limit of Propor- tionality.	Yield Point.	Maximum Stress.	Elongation Per cent. on 8 in.	Reduction of Area. Per cent.	Impact. Ft.-lbs.
		(Tons per sq. in.)				
830° C.	17·5	21·2	32·4	25·0	52·0	52
840° C.	15·6	20·0	32·6	25·0	51·0	45
860° C.	14·0	19·2	32·4	26·0	50·0	35
880° C.	13·0	18·6	31·6	27·0	52·0	26

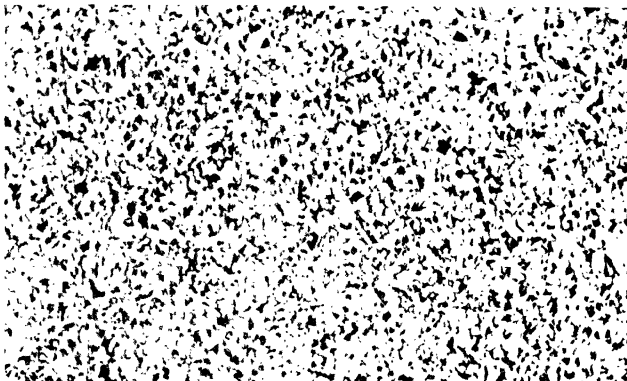


Fig. 72.—Martinel Steel Normalized 830° C. $\times 100$



Fig. 73.—Martinel Steel Normalized 860° C. $\times 100$



Fig. 74.—Martinel Steel Normalized 880° C. $\times 100$

It is evident that the limit of proportionality and yield point are closely related to the grain size, and that therefore the greatest care is required in the normalizing treatment to ensure that the best physical and mechanical properties are obtained. The value of the microscope as an indispensable part of the heat-treater's equipment is well exemplified here.

Bolts, studs, and the like are now commonly specified with a tensile strength of from 30 to 35 tons and an impact value of not less than 25 ft.-lb. A high manganese content is therefore necessary, and the bars should be normalized. Typical analysis and mechanical properties are:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.		
·25	·78	·05		
Normalized 850° C.				
Yield Point. Tons per sq. in.	Max. Stress.	Elongation. Per cent on 8 in.	Impact. Ft.-lbs.	
18·0	33·5	25·0	45	

In the quenched and tempered condition this steel is suitable for locomotive and other axles (B.S.S. 24, Part 1). After oil quenching from 880° C. and tempering at 650° C., the following results have been obtained:

	Yield Point. Tons per sq. in.	Max. Stress.	Elongation. Per cent on 3 in.	Impact. Ft.-lbs.
	28·5	38·4	30·0	55
B.S.S. 24, Part 1	50 per cent of M.S.	35/40	25/20 min.	—

Free Cutting Steel

This is a special high sulphur grade of steel for rapid turning in automatic lathes. The composition of the steel as required by B.S.S. En. 1A is as follows:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.
·07/·15	·8/1·1	·10 max.	·2/3	·07 max.

The mechanical properties of the material in the rolled condition are:

Yield Point. Tons per sq. in.	Max. Stress.	Elongation. Per cent on 2 in.	Red. of Area. Per cent.
14	27·5	36·0	55·0

Free cutting steels are usually supplied in the bright drawn condition. The effect of this cold working on the properties is discussed in Chap. X.

Group 4.—Medium Carbon Steels.

Carbon. Per cent.	Manganese. Per cent.
·25/·35	·5/·9

High-tensile plates, bars, and forgings are supplied to this analysis, the material being as rolled, normalized, or heat-treated. The B.S.S. covered by this group include No. 24, Part 4, Class C, and En. 5. The following examples illustrate the effect of heat treatment on the mechanical properties of these steels.

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
·28	·70	·10	·03	·042	
	Yield Point. Tons per sq. in.	Max. Stress. Tons per sq. in.	Elong. Per cent on 2 in.	Reduction of Area.	Impact. Ft.-lbs.
As rolled	18·0	34·0	28·0	44·0	20
Normalized, 880° C.	21·0	35·0	27·0	46·0	40
Quenched, 880° C.	32·0	44·0	25·0	52·0	50
Tempered, 600° C.					
Quenched, 880° C.	30·0	41·0	27·0	55·0	55
Tempered, 650° C.					

Group 5.—Medium Carbon Steels.

Carbon. Per cent.	Manganese. Per cent.
·35/·45	·5/·9

Bars and forgings whose surfaces have to withstand wear are made of this harder quality of steel, which may be either normalized or quenched and tempered. This latter treatment is essential if a high degree of toughness is required. As the carbon content of steel increases, the difference in properties

between normalized and heat-treated material becomes more marked. This is illustrated by the following test results.

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
·40	·72	·13	·032	·041	
	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent on 2 in.	Reduction of Area.	Impact. Ft.-lbs.
As rolled	22	41·0	24	45·0	14
Normalized, 850° C.	24	41·0	28	47·0	25
Oil quenched, 850° C. }	34	46·0	24	58·0	50
Tempered, 650° C. }					

As rolled or normalized the material complies with B.S.S. 24, Part 4, Class D, and En. 8. Heat-treated as above, it fulfils the requirements of B.S.S. En. 12.

It should be noted that these steels do not give good impact values unless in the quenched and tempered condition.

Group 6.—High Carbon Steels.

Carbon. Per cent.	Manganese. Per cent.
·45/·65	·5/1·0

Unless in the quenched and tempered condition, these steels are used only in the manufacture of parts whose primary function is to withstand wear. The hardness is obtained at the expense of ductility and toughness. The tensile strength varies between 42 and 55 tons, depending upon the thickness of section and the carbon and manganese contents. The steels are used largely for rolling stock, tyres, rails, and automobile or aircraft engine cylinders. Test results typical of the series are as follows:

Tyre Steel for Carriages and Wagons

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.	
·48	·67	·12	·041	·036	
	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent on 2 in.	Reduction of Area. Per cent.	
B.S.S. 24, Part 2 } Class B	—	42/48	18/15	—	
Tyre forged and normalized, 820° C. }	24	43	20	35	

Railway Rails

B.S.S. 9 and 11 specify the analyses and mechanical properties as follow, the rails being supplied as rolled :

			Medium Manganese.		Higher Carbon.	
			Acid. Per cent.	Basic. Per cent.	Acid. Per cent.	Basic. Per cent.
Carbon	..	..	·45/·55	·50/·60	·50/·60	·55/·65
Manganese	..	..	·90/1·2	·90/1·2	·90 max.	·90 max.
Silicon	..	..	·10/·30	·10/·30	·10/·30	·10/·30
Sulphur	..	..	·06 max.	·05 max.	·06 max.	·05 max.
Phosphorus	..	..	·06 max.	·05 max.	·06 max.	·05 max.
Maximum stress	}		46 min.		46/55	
Tons/sq. in.						
Elongation,	}		12/10		12/10	
per cent on 2 in.						

The elongation obtained is usually higher than the minimum specified, the sum of the tensile and elongation being frequently over 60 with the lower tensile, and over 65 with the higher tensile values.

A higher standard of quality is demanded of this steel when used for steel cylinders. B.S.S. S.70 includes the following requirements:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.
·50/·60	·50/·80	·10/·35

The material after normalizing at 830°/860° C. must give the following test results:

Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent on 2 in.	Brinell Hardness.
22 min.	45 min.	18 min.	192/269

The higher Brinell number limits the tensile strength to about 60 tons maximum.

Actual results obtained were:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Sulphur. Per cent.	Phosphorus. Per cent.
·56	·70	·18	·042	·032
Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent on 2 in.	Reduction of Area. Per cent.	Brinell Hardness.
26	49	21	34·5	217

PLATE 16

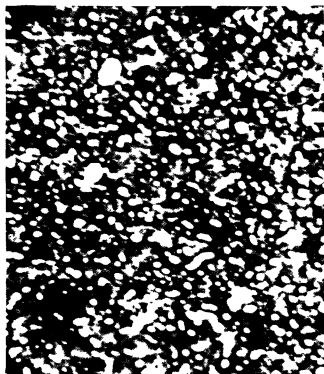


Fig. 75.—1.10 per cent C Tool Steel
W.Q. 850° C., Tempered at 700° C.
× 350

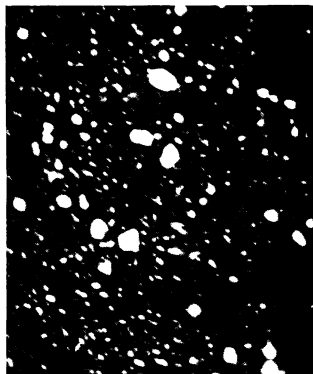


Fig. 76.—1.10 per cent C Tool Steel
W.Q. 760° C., Tempered 200° C.
× 350

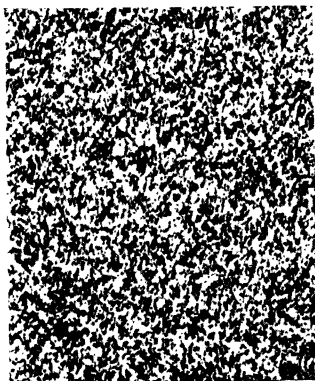


Fig. 79.—Ball-bearing Steel Oil-
quenched 820° C. × 100

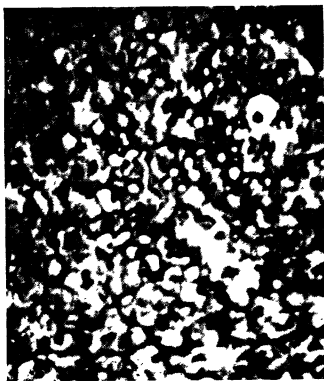


Fig. 81.—High-speed Tool Steel,
fully treated. × 1550

The same material, oil-quenched from 830° C. and tempered at 620° C., complies with the requirements of B.S.S. S.79 for heat-treated cylinder steels, as follows:

	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent. on 2 in.	Reduction of Area. Per cent.	Brinell Hardness.
B.S.S. S.79	38·5 35 min.	58·4 55 min.	22·0 15 min.	39·6 —	269 241/311

Laminated spring steels for railway and general purposes are made of steel of the following composition (B.S.S. En. 43 and 24, Part 3):

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.
·45/·65	·5/1·0	·1/·35

In neither specification is the tensile strength or heat treatment specified. B.S.S. 24, Part 3, however, provides for a cambering test.

The hardening temperature is 780° to 830° C., according to the analysis. Tempering followed by air cooling is carried out between 400° C. and 450° C. This latter treatment removes excessive strains without greatly reducing the hardness, which is usually about 350 Brinell.

Group 7.—High Carbon Steels.

Carbon, ·65/·9 per cent

Laminated springs (B.S.S. En. 42 and 24, Part 3) are manufactured from this grade of steel, and hardened in oil. With these exceptions, steels of this analysis are used exclusively for parts whose main function is to withstand severe wear or abrasion. These include riveting dies, snaps, punches, and other tools which do not require a sharp cutting edge. The parts are quenched in oil or water according to their size and the degree of hardness desired, and are thereafter reheated to a temperature usually below 350° C. to remove strains.

The hardness of such articles is conveniently measured by the Vickers Diamond Hardness testing machine or the Shore Scleroscope. The H_v values obtained vary from 630 to 960, while the Shore Scleroscope value is 75/95. Experience alone determines the most suitable value for a particular job.

Group 8.—Hyper-eutectoid Steels.

Carbon, over .9 per cent

Volute and helical springs to B.S.S. 24, Part 3, are made to the following composition:

Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.
.9/1.2	.45/.70	.30 max.

These are fully quenched in oil and tempered at a low temperature to relieve hardening strains.

In the normalized or annealed condition, hyper-eutectoid steels consist of pearlite grains surrounded by a network or film of excess cementite (fig. 32, Plate 6). The excess cementite is dissolved by austenite on heating above the upper critical point, and on quenching a pure martensite structure is obtained. When the quenched steel is tempered, the cementite forms small rounded globules distributed uniformly throughout the ferrite (fig. 75). If now the steel is heated to a temperature between the lower and upper critical points (say between 730° and 760° C.), some of these globules will not be dissolved and will remain when the steel is again quenched and re-tempered below 300° C. The final structure of the steel will then consist of martensite in which are embedded a number of globules of cementite (fig. 76). Such a steel has excellent cutting properties and is used for all kinds of cutting tools. A list of these is shown in Table XII, together with the carbon content which has been found to be most suitable for each type of tool.

TABLE XII

CARBON TOOL STEELS

Tool.	Carbon Content. Per cent
Shear Blades, Chisels, Drills, Taps, and Punches	.90/.95
Cold Chisels, Taps, Drills, Cutters, Slotting Tools, } Axes, and Picks	.95/1.1
Small Cutters, Drills, Planing Tools, Turning } Tools, and Razors	1.1/1.4

As with the lower carbon tool steels, the best treatment for a particular type of tool is a matter of experience. The tool-smith judges the tempering temperatures from the colour of the oxide film which appears on a bright surface exposed to

the air. Tables have been compiled which correlate these temper colours with the temperature, but as, for example, a light straw colour may be variously interpreted by different observers, these tables are of little value.

There is no satisfactory test other than that of service by which the cutting properties of tools may be determined or compared. Hardness *per se* does not provide a reliable indication of the wearing properties of the cutting edge. The uniform distribution of the excess cementite plays an important part, as does the design of the tool face. The shaping and heat treatment of tool steels are operations which therefore demand expert and painstaking workmanship.

CHAPTER VIII

Alloy Steels

In the previous chapter it was demonstrated that in plain carbon steels the engineer has at his disposal a choice of materials with a remarkably wide range of properties. At the same time, it must be admitted that modern developments in engineering science have so raised the standard of demand that plain carbon steels are no longer able to fulfil all requirements. For example, we have seen that a reasonably high impact value (say 30 ft.-lb.) cannot be obtained from a normalized carbon steel with a tensile strength of more than about 35 tons per square inch. Even in the fully heat-treated condition the upper limit of tensile strength, consistent with toughness, is about 45 tons per square inch. Again, the necessity of water-quenching with its attendant dangers of distortion and cracking is a severe disability; and finally, there is a narrow limit to the thickness of section which can be hardened satisfactorily when a plain carbon steel is employed. These limitations may be overcome by the simple expedient of increasing the quantity of material, and where weight is not of major importance, as in buildings and bridge work, this may still be the most economical method. But where lightness is desirable or necessary, as in automobile or aircraft construction, new materials

must be found. These new materials are the alloy steels and the light non-ferrous alloys.

These alloying metals are added to the steel to give increased tensile strength in the "as rolled" or normalized condition, and to obtain higher tensile strengths and deeper hardening in the heat-treated condition. Some alloys are also used to obtain properties not possible with carbon steels, such as resistance to scaling and corrosion, and retention of strength at elevated temperatures. The effect of the principal alloying elements on the constitution and properties of steel may be briefly summarized as follows (see also p. 62):

Manganese. Soluble in ferrite and austenite. Forms carbides. Lowers critical range on heating and cooling. Strengthens ferrite and increases hardenability.

Chromium. Soluble in ferrite and austenite. Carbide-forming tendency greater than that of manganese. Raises critical range on heating, lowers critical range on cooling. Strengthens ferrite and increases hardenability. Increases high temperature strength and resistance to corrosion and oxidation.

Nickel. Soluble in ferrite and austenite. Does not form carbides. Lowers critical range on heating and cooling. Strengthens ferrite and slightly increases hardenability. Most effective in combination with chromium. Contributes to high toughness, especially at low temperatures. (High nickel iron alloys have special thermal expansion and magnetic characteristics.)

Molybdenum. Soluble in ferrite and austenite. Strong carbide-forming tendency. Considerably increases hardenability. Increases resistance to softening on tempering. Raises high temperature strength and creep resistance (p. 127). Increases corrosion resistance in stainless steel.

Vanadium. Used only in small quantities in combination with other elements to increase hardenability, to preserve fine grain, and to resist softening on tempering.

Tungsten. Carbide-forming tendency strong. Used principally for magnet and tool steels.

Titanium. Carbide-forming tendency great, thus withdrawing carbon from solution and reducing hardenability and hardening on cold working.

Silicon. Does not form carbides. Strengthens ferrite and slightly increases hardenability.

It is not practicable to classify the alloy steels on a basis of composition, as the number of possible variations is almost countless. A convenient "first" classification is:

Group 1. Untreated low-alloy Steels

This group comprises low-alloy steels used in the "as rolled" or normalized condition, covered by B.S.S. 548, 968 and En.14. Manganese and chromium are the alloys used, the range of analysis being as follows:

	C per cent.	Si per cent.	Mn per cent.	Ni per cent.	Cr. per cent.
Manganese Steel	·30 max.	·35 max.	1·8 max.	·5 max. ¹	·35 max. ¹
Chromium Steel	·30 max.	·35 max.	·8 max.	·5 max. ¹	·8 max.

Where the steel is required for welding (B.S.S. 968) the carbon content is limited to ·23 per cent maximum.

These steels are used extensively for boiler plates for high-pressure, high-tensile plates, &c., for ships, bridges and building construction, and for general engineering purposes. Since the riveting process has a partial quenching effect the carbon content of high tensile rivet bars should not exceed ·20 per cent (see p. 54). Typical analyses and mechanical properties of the manganese steel are as undernoted:

		C per cent.	Si per cent.	Mn per cent.	Ni per cent.	Cr per cent.
A		·26	·06	1·50	·1	Nil
B		·20	·12	1·20	·35	Nil
C		·27	·15	1·5	·40	·2

			Yield Point. Tons/sq. in.	Maximum Stress. Tons/sq. in.	Elong. on 8 in. Per cent.	Red. of Area. Per cent.	Izod Impact. Ft.-lbs.
A	1½" Ship Plate "As Rolled"	<i>Spec. Cross Test</i>	22 min.	38/43	20 min.	—	—
			24·5	39·2	22	48·5	35, 31, 36
B	1½" Welding Boiler Plate. N. 850° C.	<i>Spec. Cross Test</i>	50% of M.S.	34/38	20 min.	—	—
			22	36·5	22	47·5	36, 32, 30
C	3" Dia. Bar. N. 850° C.	<i>Spec. (En.14) Cross Test.</i>	23 min.	38 min.	20 min.	—	—
			25	42·5	24	52·0	25, 26, 24

¹ The nickel and chromium are obtained from the scrap; virgin alloys are not added.

Group 2. Quenched and Tempered Structural Steels

This group comprises heat-treated alloy steels with tensile strengths of from 45 tons to over 100 tons per square inch. These include practically all the medium and high-tensile steels used for the manufacture of automobile and aircraft engines and other high-duty machinery. Before we consider the sub-classification of these steels, a few remarks on their selection and heat treatment may be useful.

It should be noted that for every range of tensile strength there is a wide choice of steels, all of which are in current use. It must be admitted that conservatism and prejudice maintain the demand for certain steels which technical advances and economic considerations would have rendered obsolete. The dearest steel is not necessarily the best. Recent work has demonstrated that, in general, triple or quadruple alloy steels are, for the quantity of alloys used, the most efficient in depth-hardening properties, and such steels will be increasingly used as experience proves their reliability. Another advantage of these steels lies in the fact that much of the steel scrap returned to melting shops contains varying amounts of nickel, chromium and molybdenum, and considerable economies can be effected if these form the basis of the alloy steels.

Janitzky and Baeyer¹ have shown that for steels which have been fully hardened, the yield point, elongation, and reduction of area in the hardened and tempered condition depend on the ultimate tensile strength and are independent of the composition of the steel. This does not apply to notch toughness, particularly at low temperatures. For a given ultimate tensile strength the notch toughness at normal and low temperatures is generally greater the lower the carbon content. Nickel steels are also said to be particularly suitable where notch toughness at low temperatures is necessary.

When steel is to be welded a low carbon content is necessary (see Chap. XII). Other factors to be considered in the selection of material are wear resistance (which depends on other things besides hardness), forgeability, and machinability. Apart from these considerations, and where mechanical properties are the chief desiderata, one steel is as good as another.

The tensile range for which a particular steel is suitable

¹ *Metals Handbook* (American Society for Metals) 1939, p. 515.

depends, of course, upon the thickness of section at the time of quenching and upon the response to tempering. As already mentioned (p. 55) reasonable impact values are not obtained with tempering temperatures below 500°C . This is illustrated in Table XIII and fig. 77, which also shows an important

TABLE XIII

THE RELATION BETWEEN TEMPERING TEMPERATURES AND
IMPACT VALUES OF NICKEL-CHROME STEEL

Carbon. Per cent.	Manganese. Per cent.	Nickel. Per cent.	Chromium. Per cent.
·34	·5	1·6	1·14

Oil-quenched, 830°C ., tempered for 15 min., quenched in water.

Tempering Temperature, $^{\circ}\text{C}$.	Brinell Hardness Number.	Izod Impact. Ft.-lbs.
100	514	8
150	495	8
200	477	12
250	477	14·5
300	444	4·5
350	444	4
400	415	9
450	363	21·5
500	331	34
550	311	55
600	293	60
650	277	80

feature common to many alloy steels, viz. that on tempering above 250°C . the impact value decreases and begins to increase again only if the tempering temperature approaches $350/400^{\circ}\text{C}$. For this reason alloy steels are never tempered in the range $250/450^{\circ}\text{C}$. Although the impact rapidly increases above this latter temperature, in general the minimum tempering temperature for alloy structural steels is 520°C .

From the foregoing it will be understood that classification according to ultimate tensile strength is not possible unless at the same time the size of section is taken into consideration. This can most conveniently be done diagrammatically. Fig. 78 shows for each of ten types of steel the minimum ultimate tensile strength consistent with satisfactory ductility which can be obtained from quenched and tempered sections of from 1 in. to 6 in. dia. For most of these types of steel there

is a wide choice of suitable compositions, of which Table XIV is merely a selection. It will be noted that there is a wide range of analysis for each steel. In general the higher limits

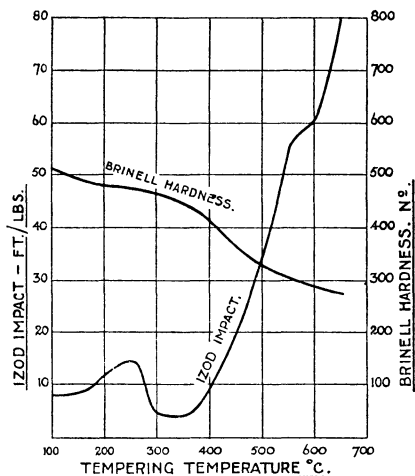


Fig. 77.—The Relation between Tempering Temperatures and Impact Values of Nickel-chrome Steel

of analysis are chosen for material of heavy section. Routine hardenability tests are carried out to ensure that the material is satisfactory for the job required (see p. 64). It will also be

TABLE XIV

ANALYSES OF SOME EN. STEELS (B.S. 970)

No.	En. Spec.	C Per cent.	Mn Per cent.	Ni Per cent.	Cr Per cent.	Mo Per cent.
1	15	·30/·40	1·30/1·70	—	—	—
2	18	·35/·45	·60/·95	—	·80/1·10	—
3	100	·35/·45	1·20/1·50	·50/1·00	·30/·60	·15/·25
4	110	·35/·45	·40/·80	1·20/1·60	·90/1·40	·10/·20
5	24	·35/·45	·45/·70	1·30/1·80	·90/1·40	·20/·35
6	23	·25/·35	·45/·70	2·75/3·50	·50/1·00	·65 max.*
7	28	·25/·40	·70 max.	3·0/4·50	·75/1·50	·20/·65
8	25	·27/·35	·50/·70	2·30/2·80	·50/·80	·40/·70
9	26	·36/·44	·50/·70	2·30/2·80	·50/·80	·40/·70
10	30B	·26/·34	·40/·60	3·90/4·30	1·10/1·40	·20/·40

* Optional.

noted that for any given section, the higher the ultimate tensile strength the more highly alloyed is the steel. The higher alloy steels with further tempering will, of course, give a lower tensile strength than that shown. The point to be emphasized

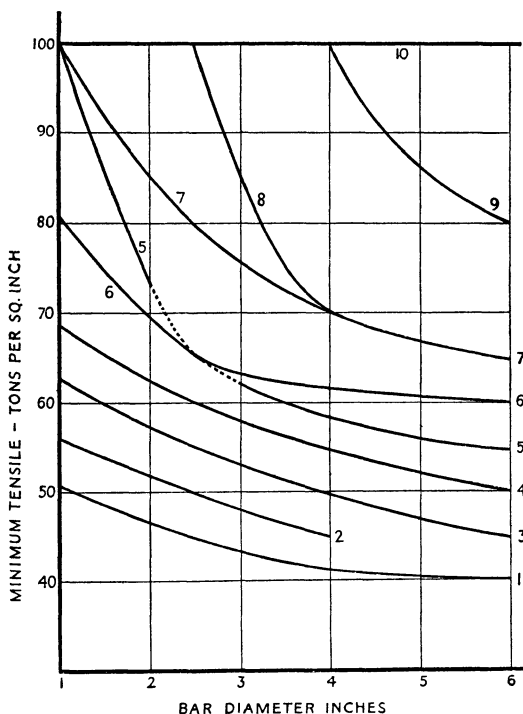


Fig. 78

is that there is nothing to be gained by using a higher alloyed steel for a given ultimate tensile strength and section than that shown in fig. 78.

For each type of steel the tensile strengths specified for the various diameters have been so chosen that the other mechanical properties (yield point, elongation and impact) are satisfactory, and the specification of these properties is deter-

mined by the ultimate tensile strength only. The mechanical properties obtained vary a little with bar diameter, the yield ratio and the impact values decreasing slightly as the bar diameter increases. The mechanical properties specified and normally obtained for the various tensile ranges are shown in Table XV. One example only is shown for each tensile range, but as explained above this gives sufficient indication of the properties to be expected for any bar from any steel quenched and tempered to the ultimate tensile strength shown.

When the tensile strength is over 65 tons per square inch the material is not easily machined, and it is customary to carry out most of the machining of the steels in the softened condition, the finish machining being done after the material has been hardened. For steels over 80 tons tensile the machining is so difficult that the tensile test pieces are machined to size before heat treatment. The hardenability curves of such steels, although not necessarily representing the test results to be obtained on all sizes, show that the hardening is uniform within the size limits for which the steels are recommended.

The higher alloy steels demand the utmost care in hot working and heat treatment. Heating for forging should be slow, and after forging very slow cooling is necessary, particularly when the forging is of unequal section. Slow cooling still leaves the steel in a hardened condition, and softening for machining is carried out by heating to 630–650° C., soaking for 2–4 hours and cooling in air or in the furnace. In quenching, either the oil or the steel should be agitated to ensure uniform hardening, and as has already been mentioned, tempering should be carried out as soon as possible thereafter. Again it must be emphasized that sharp corners invite quenching cracks.

Group 3.—Steels for Special Purposes

Although a large amount of research has been carried out on the constitution of the alloys of iron with other metals, the fact remains that the suitability of any particular alloy for any particular purpose is a matter which can be decided only by direct experiment. This does not mean that experimental work on alloy steels is carried out in a haphazard, hit-or-miss manner, for systematic research has determined the *kind* of properties obtainable from most of the common elements when alloyed with iron. For example, the effects of chromium

TABLE XV

Tensile Range.	Material.	Max. Stress. Tons/sq. in.	Yield Point. Tons/sq. in.	Elongation on 2", Per cent.	Izod Impact. Ft.-lbs.
40-50	Spec. 3½" dia. En.15 O.H. 860° C. t. 620° C.	—	30	22	40
	Spec. 3" dia. En.18 O.H. 850° C. t. 640° C.	43	34	26	75, 80, 76
45-55	Spec. 3" dia. En.18 O.H. 850° C. t. 640° C.	—	34	22	40
	Spec. 3" dia. En.18 O.H. 850° C. t. 640° C.	51	41	23	73, 71, 70
50-60	Spec. 3" dia. En.100 O.H. 850° C. t. 620° C.	—	38	20	40
	Spec. 3" dia. En.100 O.H. 850° C. t. 620° C.	57	48	22	50, 58, 53
55-65	Spec. 2" dia. En.100 O.H. 850° C. t. 620° C.	—	44	18	40
	Spec. 3" dia. En.24 O.H. 850° C. t. 650° C.	61	50	21	48, 52, 46
60-70	Spec. 3" dia. En.24 O.H. 850° C. t. 650° C.	—	48	17	35
	Spec. 1½" dia. En.110 O.H. 850° C. t. 610° C.	65	55	22	52, 54, 50
65-75	Spec. 1½" dia. En.110 O.H. 850° C. t. 610° C.	—	52	16	35
	Spec. 4" dia. En.110 O.H. 830° C. t. 550° C.	70	58	20	52, 51, 48
70-80	Spec. 3" dia. En.28 O.H. 830° C. t. 530° C.	—	58	15	30
	Spec. 3" dia. En.28 O.H. 830° C. t. 530° C.	74	62	19	44, 48, 50
75-85	Spec. 3" dia. En.28 O.H. 830° C. t. 530° C.	—	63	14	25
	Spec. 3" dia. En.28 O.H. 830° C. t. 530° C.	77	68	19	50, 46, 44
80-90	Spec. 564" dia. En.28 O.H. 840° C. t. 540° C.	—	68	14	25
	Spec. 564" dia. En.30 A.H. 820° C.	84	79	17	42, 38, 40
100 min.	Spec. 564" dia. En.30 A.H. 820° C.	—	85	10	10
		110	98	14	24, 22, 20

on the corrosion resistance (and their cause), and of cobalt on the magnetic properties, have been fully investigated, with the result that chromium is regarded as an essential constituent of corrosion-resisting steels, and cobalt of high quality permanent magnets. The properties obtained by the addition of a single alloying element, however, are modified by the addition of varying quantities of a second, third, or even fourth alloy, so that the number of alloy steels which are worth while investigating remains enormous. The compositions of the special alloy steels marketed from time to time depend to an appreciable extent on the availability and price of the necessary raw materials, and, in some cases, on the desire to provide "something different" as a basis of sales talk.

An extensive discussion of these special steels is, therefore, impossible as well as futile. A description of a few of the commoner types is all that is attempted here, and these are classified according to the purposes for which they are required.

Steel for Bearings

Ball and roller bearings and ball races are usually supplied in accordance with B.S. En.31, the composition of which is as follows:

Carbon.	Silicon.	Manganese.	Chromium.
·90/1·2%	·1/·35%	·30/·75%	1·0/1·6%

The steel is softened for machining purposes to give a Brinell hardness of 200 or less by heating to 780° C., soaking for 10 hours and cooling slowly to 500° C. Oil hardening at 810° C. is usually followed by tempering below 200° C., the final hardness being about H_p 800/850. Tempering above 200° C. results in a serious loss in hardness.

Ball-bearing steels must be particularly clean and free from large inclusions. The structure requires to be very fine to ensure uniform hardness throughout (fig. 79, Plate 16).

Spring Steels

Silico-manganese steels are used for laminated springs for railway rolling-stock, and for road vehicles. The analyses of B.S. steels are as undernoted:

Specification.	Type.	Carbon.	Silicon.	Manganese.
B.S. En.45 and 24, Part 3.	Oil Hardening	·50/·60	1·5/2·0	·60/1·0
B.S. En.46 and 24, Part 3.	Water Hardening	·33/·50	1·5/2·0	·60/1·0

The steels are hardened from 900° C. and tempered at 450° C. to give a Brinell Hardness of approx. 450. Camber tests are as specified for plain carbon steels.

Engine valve spring steel wire for aero-engine purposes is made from a chrome-vanadium steel as follows:

	C Per cent.	Si Per cent.	Mn Per cent.	Cr Per cent.	V Per cent.	S Per cent.	P Per cent.
B.S. En.50	·40/·50	·10/·35	·50/70	1·0/1·50	·15 min.	·04 max.	·04 max.

and the finished coil is oil-quenched from 850° C. to give a tensile strength of from 90 to 110 tons per square inch.

Tool Steels

Alloy tool steels have two advantages over plain carbon steels. Firstly, they are usually satisfactorily hardened in oil, and are thus less liable to form cracks, and secondly, they are not so readily softened by heat, while plain carbon steels are easily softened by heating even for a short time, and this is unavoidable in use. Cutting edges are thus blunted and require frequent grinding. Chromium or tungsten, being carbide-forming elements, are usually employed in alloy tool steels. Table XVI gives the composition, heat treatment, and uses of some of them.

The high-speed tool steels present some unusual features which may be briefly discussed. The cast structure consists of martensite crystals surrounded by a network of complex carbides. Unless these carbide envelopes are completely broken up in the forging operation there will be considerable danger of cracking and splitting of the tool in hardening or in service.

Heating for forging must be done slowly to avoid clinking, to which these steels are particularly prone. Clinking is a sudden internal fracture (which may not become evident till the tool fails in service) and is caused by severe internal stress. This is most likely to occur when steels of low thermal conductivity, or in an intensely hard condition, are heated too

TABLE XVI

ALLOY TOOL STEELS: COMPOSITION						
Steel No.	Carbon. Per cent.	Manganese. Per cent.	Silicon. Per cent.	Nickel. Per cent.	Chromium. Per cent.	
1	.50/.60	.5/.8	.1/.3	1.25/1.75	.5/.8	
2	.30/.36	.4/.7	.1/.3	3.0/3.6	.6/1.0	
3	.36/.40	.3/.4	.1/.3	1.9/2.0	1.0/1.1	
4	.60/.75	.3/.4	.1/.3	—	.5/.6	
5	.40/.50	.6/.8	1.6/2.0	—	—	
6	.8/.9	.25/.40	.1/.3	—	1.9/2.1	.85/1.0
7	.65/.75	.25/.35	.1/.3	—	3.25/4.25	.75/1.25
8	.82/.90	.25/.35	.1/.3	3.5/4.5 Mo.	3.75/4.25	1.4/1.7 .5/1.5
HEAT TREATMENT						
Steel No.	Softening, ° C.	Hardening, ° C.	Quenching Medium.		Tempering, ° C.	Uses.
1	630	800/830	Oil		up to 630	Die Blocks.
2	630	830/850	Oil		up to 630	Die Blocks.
3	anneal, 850	800	Oil		200	Shears, Blades, Cutters.
4	anneal, 800	760	Water		200	Chisels and Punches.
5	anneal, 840	950	Water		200	Chisels.
6	anneal, 800	800	Oil		—	Heavy Cutting Tools.
7		see text			—	High-speed Tool Steel.
8		see text			—	4/4/6 H.S. Tool Steel.

quickly. The forging temperature is approximately 1200/1250° C. The actual temperature is of vital importance, as are all the temperatures involved in treating these steels, and they depend within close limits upon the analysis. Cooling after forging must be done very slowly, as also must the reheating for softening (800°/830° C. for 4 hours). Again they are cooled very slowly and are then soft enough for machining.

If quenched in oil from any temperature above 950° C. high speed tool steels are quite hard, but as cutting steels they are no better than plain carbon tool steels unless they are quenched from 1200/1270° C. The heat treatment cycle is of particular interest, since it exemplifies most of the principles of heat treatment applicable to all steels.

1. *Heat slowly to 870° C.*—This temperature is just above the upper critical point, so that after a short period of soaking the structure is austenitic with undissolved carbide particles uniformly distributed.

2. *Heat as rapidly as possible in a non-oxidizing atmosphere to 1250° C. and soak for 5 minutes.*—This dissolves the carbides, and the structure is now pure austenite. Decarburization must be avoided, since the steel is not subsequently machined and carbides are an essential part of the cutting-tool face. Underheating results in undissolved carbides. Overheating or too long soaking may cause burning.

3. *Quench in oil or air according to size of section.*—There are two modifications of this treatment designed to reduce the severe stresses set up by quenching:

(a) Cool in salt bath to 600° C. until temperature is uniform, then quench in oil.

Since the austenite/martensite transformation is negligibly slow at 600° C., the only effect of this treatment is to reduce the temperature gradient from outside to centre on subsequent quenching.

(b) Oil quench to 425° C., then air cool to room temp.

This treatment also ensures a low temperature gradient between surface and centre at the austenite/martensite transformation (200° C. and below).

The above treatments result in a structure consisting of 80 per cent martensite and 20 per cent untransformed austenite.

Two other quenching treatments may be employed:

(c) Quench in oil to 150°C . and temper immediately.

In the quenched condition about 35 per cent of the austenite remains untransformed.

(d) After quenching to room temp. re-quench to -80°C .

This treatment, known as sub-zero cooling, results in a partial transformation of the retained austenite, so that only about 10 per cent remains untransformed.

4. *Tempering*.—The tempering temperature required to give the maximum hardness depends upon the previous quenching treatment. This is illustrated in fig. 80, which shows the effect of tempering for half an hour at various temperatures for three of the quenching conditions above described. Tempering is followed by air cooling. During heating to and soaking at the tempering temperature, martensite is slightly softened, and on cooling most of the remaining austenite is transformed. As is shown in fig. 80, the final result is a harder steel. Except for treatment (d), a second tempering is usually necessary to transform the remaining austenite. Increased toughness with little loss in hardness is obtained by

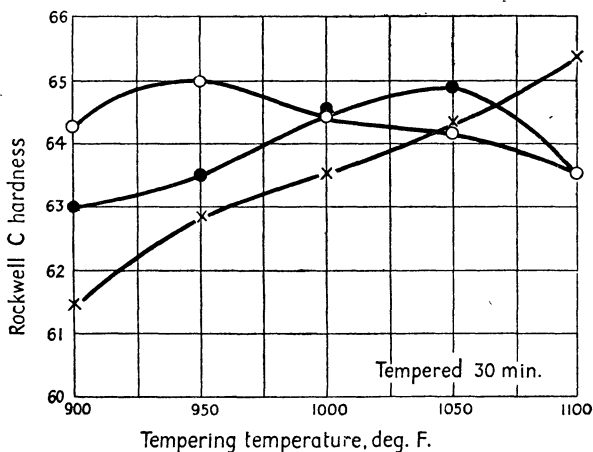


Fig. 80¹

○ Cooled to -110°F . (-80°C .) prior to tempering.

● Cooled to 70°F . (20°C .) prior to tempering.

× Cooled to $250/300^{\circ}\text{F}$. (150°C . app.) prior to tempering.

¹ *Iron Age*, March 23, 1944, p. 55.

a further tempering treatment. The structure of properly hardened and tempered high-speed tool steel is illustrated in fig. 81, Plate 16.

The 4/4/6 high-speed tool steel was developed as a result of the shortage of tungsten and has proved an excellent substitute for the 17 per cent tungsten steel. It requires more care in treatment, as it decarburizes more readily, and heat-treatment temperatures are more critical.

Magnet Steels

The magnetic properties of steel are described in terms of permeability, saturation, remanance, and coercive force.

Magnetically soft materials for the cores of transformers, pole pieces, &c., should have a high permeability and saturation value, and a very low coercive force. Pure iron is ideal, but unfortunately is not producible commercially. The material most commonly used is a 3-4 per cent silicon steel with carbon, manganese and other elements as low as possible. The magnetic properties of this material are considerably enhanced by controlled heat treating and cold rolling in one direction only. Special alloys with high nickel and cobalt contents have limited application, owing to their high cost.

Permanent magnets require a high remanance and a high coercive force. Whatever steel is employed must be in the fully hardened condition to give the required results. The steels used contain one or more of the alloying elements, chromium, cobalt, and tungsten. Some compositions are shown in Table XVII.

TABLE XVII

ANALYSES OF TYPICAL PERMANENT MAGNET STEELS

C per cent.	Mn per cent.	Si per cent.	Ni per cent.	Al per cent.	Co per cent.	Cu per cent.	Cr per cent.	W per cent.	Mo per cent.	Ti per cent.
1.00	0.4	0.2	0.2	—	—	0.05	0.05	—	—	—
0.90	0.3	0.15	0.1	—	—	0.05	2.5	—	—	—
0.67	0.3	0.15	0.1	—	—	0.05	0.4	6.0	—	—
0.85	0.5	0.15	0.1	—	35.0	0.05	6.0	4.0	—	—
0.06 (max.)	0.2	0.1	14.0	8.0	24.0	3.0	0.1 (max.)	—	—	0.2

The last is a special alloy known as Alnico V, with exceptionally high remanence and coercive force.

Non-magnetic Steel

Any steel which consists of austenite is non-magnetic. Certain highly alloyed steels are austenitic at room temperature in the "as rolled" or annealed conditions. One such steel has the following composition:

Carbon.	Manganese.	Nickel.	Chromium.
20/40%	7/8%	4·5/5%	7/8%

In the "as rolled" condition the steel has a Brinell Hardness of approx. 250 and a permeability of 1·005, and unlike most non-magnetic steels it is relatively easily machined.

Hadfield's manganese steel containing approx. 1 per cent carbon and 14 per cent manganese may be rendered austenitic and non-magnetic at room temperature by quenching from approx. 1000° C. Severe cold work, however, renders the steel martensitic, magnetic and very hard. This steel was originally developed for its excellent wear-resisting properties.

Stainless Steels

The corrosion of steel may be prevented or minimized by providing suitable protective coatings such as paint, zinc (galvanizing) and tin, or by modifying the composition to make the steel itself more resistant. Structural steels are now frequently specified to contain up to 0·6 per cent copper. This addition has no appreciable effect on the mechanical properties, but it increases two or threefold the resistance to attack by sea-water, and by city atmospheres which are usually contaminated with sulphurous gases. Corten steel, which was developed in the U.S.A., is claimed to be two or three times more resistant to atmospheric corrosion than copper-bearing carbon steels. The composition and mechanical properties of Corten steel are as undernoted.

C	Mn	P	S	Si	Cu	Cr
Per cent.	Per cent.	Per cent.	Per cent	Per cent.	Per cent	Per cent.
·10 max.	·10/·50	·10/·20	·05 max.	·5/1·0	·3/·5	·5/1·50
Yield Point.		Max. Stress.		Elongation		
Tons/sq. in.		Tons/sq. in.		Per cent on 8 in.		
22·0 min.		31·0 min.		20·0 min.		

It will be noted that this steel has a yield point approaching that of high-tensile structural steel (B.S. 548 and 968). The

TABLE XVIII

STAINLESS STEEL

Steel	C Per cent.	Si Per cent.	Mn Per cent.	Ni Per cent.	Cr Per cent.	Type
En.56A	.15 max.	.1/1.0	1.00 max.	1.0 max.	12.0 min.	Martensitic.
En.56	.15/.35	.1/1.0	1.00 max.	1.0 max.	1.20 min.	Martensitic.
En.57	.25 max.	.1/1.0	1.00 max.	1.0 min.	15.5/20	Martensitic.
En.58A	.20 max.	.2 min.	1.00 max.	8/10	16/20	Austenitic.
TAC.33E	.20 max.	.2 min.	1.00 max.	14/22	20/26	Austenitic.

HEAT TREATMENT AND MECHANICAL PROPERTIES

Steel	Treatment.		Yield Point. Tons/sq. in.	Max. Stress. Tons/sq. in.	Elongation. Per cent.	Izod. Ft.-lbs.
En.56A	O.H. 950° C.	T. 730° C. W.Q.	30	38	32	80
En.56	O.H. 970° C.	T. 650° C. W.Q.	43	53	24	35
En.57	O.H. 1000° C.	T. 620° C. W.Q.	51	58	21	50
En.58	A.C. 1050° C.		18	50	50	100
TAC.33E	A.C. 1050° C.		24	44	45	80

low carbon content ensures excellent welding properties with ordinary mild steel electrodes (see Chap. XII).

While the foregoing types of steel have proved useful in structural work such as bridges, gas-holders, railway wagons and tanks, resistance to more corrosive influences, such as are encountered in internal-combustion engines and in the chemical industries, can be obtained only with steels containing not less than 12 per cent of chromium. The wide variety of corrosive conditions met with has resulted in a corresponding variety in the steels classified as stainless. The chromium ranges from 12 to 26 per cent, the nickel from nil to 37 per cent, while molybdenum may be present up to 3 per cent. The higher alloyed steels are required not only for their resistance to corrosion but particularly for their mechanical properties and resistance to oxidation at high temperatures.

The stainless steels may be divided into two main classes:

(1) Martensitic Steels, (2) Austenitic Steels.

The composition, treatment and mechanical properties of some typical steels are shown in Table XVIII. The mechanical properties are obtained from sections up to $3\frac{1}{2}$ in. diameter. Sulphur, phosphorus and selenium may be added to these steels to improve machinability.

Heat-resisting Steels

Two problems arise in the application of steel to high temperature service. One is "creep" (see Chap. XI) and the other oxidation or scaling. In air or other oxidizing atmospheres ordinary carbon and low alloy structural steels begin to scale appreciably above 530°C . "Heat-resisting Steels" are those steels which do not oxidize so readily as do carbon steels. The higher the temperature, the greater the rate of oxidation, so that different types of steels have been developed for service not exceeding specified temperatures. Chromium and silicon are the alloying metals used to confer heat-resisting properties, and the carbon content of these steels should be low. Molybdenum is an essential constituent when resistance to creep is important. A few of such steels showing the maximum temperature at which the material will have a useful life are listed in Table XIX. The low alloy steels in this series have been developed to give also good mechanical properties at high temperatures. None of the high chromium steels (stainless type) give satisfactory mechanical properties at

TABLE XIX

HEAT RESISTING STEELS

C	Si	Mn	Ni	Cr	Mo	Heat Treatment.	Max. Service Temperature.
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.		
.15 max.	1/1.5	.5 max.	—	1 (approx.)	.5 (approx.)	As Rolled	620° C.
.15 "	1/1.5	.5 "	—	2 "	.5 "	As Rolled	650° C.
.15 "	.5 max.	.5 "	—	4/6	.5 "	As Rolled	650° C.
.15 "	1/2	.5 "	—	4/6	.5 "	As Rolled	700° C.
.15 "	.1/1.0	1.0 "	1.0 max.	12.0 min.	—	Quenched and Tempered	750° C.
.15 "	.1/1.0	1.0 "	8/10	16/20	—	N. 1050° C.	900° C.
.20 "	.2 min.	1.0 "	14/22	20/26	—	N. 1050° C.	1000° C.

high temperatures, but with the addition of not less than $2\frac{1}{2}$ per cent molybdenum the 8/10 per cent nickel—16/20 per cent chromium steel gives excellent creep properties up to 650°C .

CHAPTER IX

The Surface Hardening of Steel

In the previous discussions on the manufacture and heat treatment of steel, emphasis has been placed on the importance of uniformity, both of composition and of properties, throughout the material. There are, however, two applications for which it is advantageous to depart from this principle. In the first, certain parts of machinery are required to withstand abrasion or wear, and a hard surface is therefore essential. Unfortunately, the harder the steel is made the more brittle it becomes, and the degree of hardness necessary to withstand abrasion far exceeds that which can be obtained from a "tough" steel. Since abrasion is confined to the surface, the solution of the problem lies in providing a hard surface and a tough core. The second application arises from the discovery that the fatigue resistance of steel is greatly increased by increasing the hardness of the surface layers. The surface hardening of steel is, therefore, an important branch of ferrous metallurgy, and new techniques are constantly being explored and developed.

Two definite principles are applied. In the one the hardness is obtained by adding carbon or nitrogen to the case; in the other the material remains uniform in composition, but by a special heat treatment process the surface layers only are fully hardened. The following is a brief description of surface-hardening processes; pack carburizing is discussed in greater detail, since this is not only the oldest but also the most generally useful method of surface hardening.

Pack Carburizing

This operation depends upon the absorption of carbon by steel at temperatures above the upper critical temperature. The carburizing materials used consist of carbonaceous com-

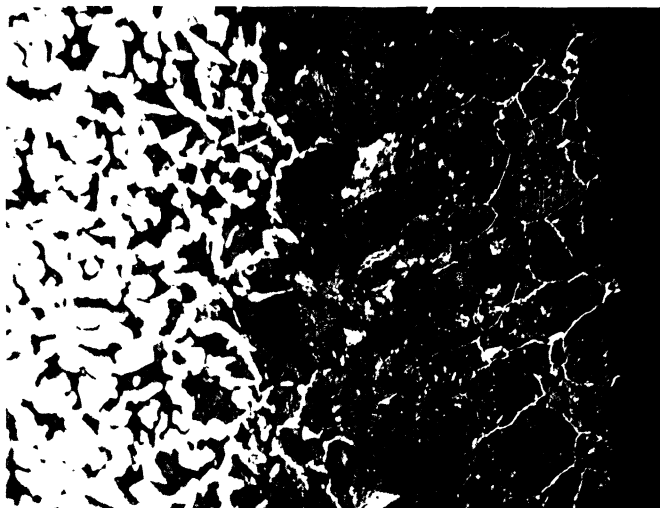
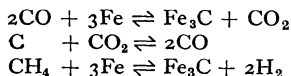


Fig. 82.—Case and Core of Carburized Bar



Fig. 85.—Fracture of Case-hardened Bar. $\times \frac{1}{2}$

pounds in the form of wood or animal charcoal, charred leather, and petroleum coke with about 20 per cent of alkaline or metallic carbonates, together with a carbonate energizer, usually barium carbonate. At the carburizing temperature this mixture generates principally carbon monoxide and some hydrocarbons, and it is these gases, and not the solid carbon, that react with the steel, forming cementite. The reactions are essentially as follows:



The articles to be case-hardened are finish-machined, with (if desired) an allowance for subsequent grinding, before being packed in the carburizing material in suitable boxes or containers. The boxes are covered with lids, which must be sealed to prevent the escape of the gases and the admission of air. It will be readily understood that the composition of the carburizing material is important, and since this compound is partially consumed, new material should be added before using again. The efficiency of the mixture is determined principally by:

1. The rapidity of its carburizing action on the steel.
2. Thermal conductivity, which should be relatively high, so as to cut down carburizing time.
3. Shrinkage; large shrinkage leads to heavy distortion of the steel parts, because of the resultant inadequacy of support when they are in a soft plastic condition.
4. Freedom from dust, which if present in excess tends to cake and so cause non-uniformity of carburizing action, resulting in soft spots in the case. Free circulation of the gases is essential for uniform carbon penetration.

The mechanism of carbon absorption by steel may be examined by considering a plain carbon steel containing .15 per cent carbon. At the carburizing temperature, 900° C. to 950° C., the steel consists of austenite, in which, as has been shown, cementite is soluble up to 1.8 per cent. It follows therefore that the cementite which is formed at the surface of the steel by the action of the carburizing mixture will dissolve in the underlying layer of metal. Now it is the nature

of all solutions, whether liquid or solid, that any substance dissolved in them tends to diffuse until its concentration is uniform throughout. This means that the cementite will move inwards from the surface, and the speed of this movement will depend on the temperature—the higher the temperature the greater the speed. At the same time, for a given carburizing mixture the higher the temperature the more rapid will be the formation of cementite at the surface of the steel. The formation of the case in this manner leads to a gradient in the carbon content, which is highest at the surface and gradually decreases as the case merges into the core (fig. 82, Plate 17). The carbon content of the case should not greatly exceed that for eutectoid composition. Higher carbon content offers no advantage, and has certain disadvantages, discussed in the section on "Heat Treatment after Carburizing". The carburizing temperature should therefore never exceed 950°C ., otherwise there is a tendency for cementite to be formed at the surface of the steel much quicker than it can diffuse, thus resulting in a high concentration of carbon in the case.

The depth of the case is important. In practice this may vary from about $\cdot 01$ in. in lighter articles to as much as $\cdot 15$ in. or even deeper in heavier work, such as roller bearings or ball races where the compressive stresses are high. Other things being equal, the depth of the case depends upon the carburizing period, but unfortunately there is a tendency for deep cases to contain an excess of carbon unless the temperature is kept low. For most purposes a case depth of about $\cdot 05$ in. is satisfactory, and this can be obtained under normal working conditions at a temperature of 925°C . in a period of five to eight hours.

It will now be clear that the carburizing operation is one demanding careful control if the best results are to be expected. Where possible the carburizing mixture should be standardized and all fresh deliveries tested. Temperatures should always be controlled by means of reliable thermo-couples placed in the furnace in order to standardize heating times. The type of furnace, the shape of the boxes, and their position in the furnace, are other important factors which influence the uniformity of the product. When the operation is completed the boxes are allowed to cool down to room temperature before withdrawing the steel. It is advisable before unpacking

to check the depth of the case by quenching a small test piece in water and examining the fracture. This same test piece will also serve for a micro-examination from which valuable information may be obtained. Indeed, the microscope provides the best means of control throughout the entire case-hardening process.

Selective Carburization

For certain special purposes it may be desirable to retain a portion of the surface in the unhardened condition. This may be accomplished by one or other of the following methods:

1. *Excess metal is left at portions desired soft.* After the carburizing operation the excess which has been carburized is machined off to below the case depth. This method is particularly useful where threads or sharp corners are to be left soft.
2. Tapped holes and bores of gears, for example, may be blocked with a cement consisting of two parts fire-clay, one part sodium silicate and $\frac{1}{10}$ part of water. After carburizing the cement may be easily removed from the holes.
3. The parts to be retained soft may be protected by a deposit of copper. For short carburizing periods the deposit obtained by dipping in copper sulphate solution may be sufficient, but for longer periods electrolytically deposited copper may be necessary.

Heat Treatment after Carburizing

The structure of the steel as carburized is illustrated in fig. 82. Prolonged exposure to a high temperature has caused considerable grain growth in both the case and the core. The larger grains of the case compared with those of the core provide an interesting demonstration of the effect of carbon on the position of the critical temperatures. Grain growth is rapid after passing the upper critical temperature, or A_{c3} , and it will be observed from the iron-carbon diagram (p. 28) that this temperature is much lower for the case containing say 0.9 per cent carbon than for the core containing .15 per cent carbon. Consequently, at the carburizing temperature (900° to 950° C.) grain growth is accelerated to a greater extent in the case than in the core. It will also be observed (fig. 82)

that there is a network of free cementite which has separated out around the boundaries of the grains in the surface layers during the slow cooling in the box. The heat treatment of the carburized steel therefore consists of a refining of the core and a refining and hardening of the case.

Core Refining

This is accomplished by normalizing or quenching, and from the iron-carbon diagram (see p. 28) the correct temperature for the core (.15 per cent carbon) is found to be 900° to 920° C. The method of cooling from this temperature has practically no influence on the grain size; it has, however, an important effect in other directions. A quick cooling rate increases the tensile strength of the core, and what is more important, it eliminates the dangerous brittle network of cementite in the case. At a temperature of 900° C. all the free cementite will be dissolved by the austenite unless the carbon content of the case is much higher than it should be, and so by rapid cooling an opportunity is afforded of preventing this constituent from separating out again in this manner. For these reasons it is the general practice whenever possible to quench the steel in water from the refining temperature. Fig. 83, Plate 18, shows the structure of the core after refining.

Case Hardening

To obtain the maximum hardness of the case, water hardening is necessary. The hardening temperature depends upon the carbon content and is lowest when this gives a steel of eutectoid composition. With higher carbon a higher temperature is necessary to dissolve the carbides, and subsequent quenching may give untransformed austenite, resulting in reduced hardness. Also it is important that the case hardening treatment should not affect the properties of the previously refined core, and for this reason also the hardening temperature of the case should be as low as possible, and the heating carried out as rapidly as possible. A hardening temperature of 760° C. should be adequate if the carbon content of the case is not excessively high. The structure of the case-hardened part is illustrated in fig. 84, and typical mechanical properties of the core are given in Table XX.

The carbon content of the core of carburized steel is kept as low as possible for two reasons. Firstly, as explained above,

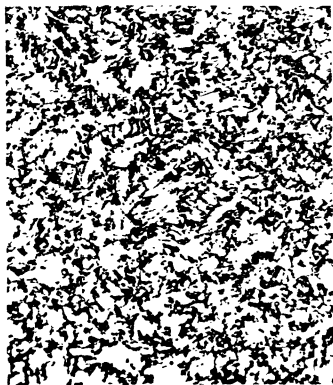


Fig. 83.—Case-hardened Bar—Core,
Refined. $\times 130$

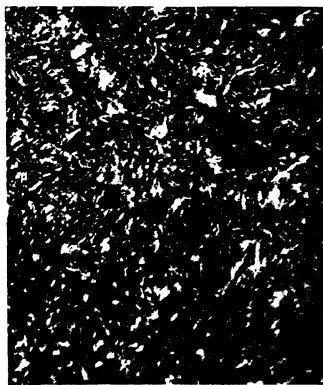


Fig. 84.—Case-hardened Bar—Case,
Refined and Hardened. $\times 130$

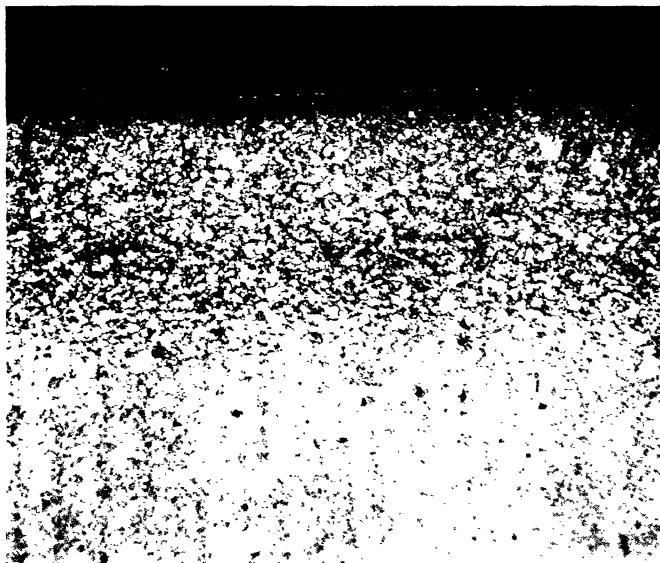


Fig. 90.—Nitrided Case. $\times 100$

TABLE XX

TYPICAL ANALYSES OF CASE-HARDENING STEELS

Description.	C	Mn	Si	S	P	Ni	Cr	Mo	Specification
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	
.15 per cent Carbon	0.15	0.63	0.17	0.038	0.028	0.20	0.10	—	B.S. En.32
3 per cent Nickel	0.14	0.38	0.20	0.038	0.021	3.35	0.13	—	B.S. En.33
2 per cent Nickel-Moly.	0.16	0.40	0.21	0.029	0.018	1.75	—	0.25	B.S. En.34
3 per cent Nickel-Chrome	0.13	0.48	0.25	0.035	0.026	3.50	0.81	—	B.S. En.36
4½ per cent Nickel-Chrome	0.16	0.35	0.18	0.015	0.020	4.30	1.35	0.15	B.S. En.39

MECHANICAL PROPERTIES OF CASE-HARDENED STEELS

Description	Blank Carburized	Treatment on 1½-in. Dia. Bar.		Mechanical Properties of Core.			Impact.
		Refined.	Hardened.	Yield Point.	Maximum Stress.	Elongation. Per cent. on 2 in.	Ft.-lbs.
		Tons/sq. in.	Tons/sq. in.	Tons/sq. in.	Tons/sq. in.		
.15 per cent Carbon	900/950° C.	900° C. W.Q.	760° C. W.Q.	25.3	34.7	31.0	88
3 per cent Nickel	900/950° C.	860/870° C. W.Q.	760° C. W.Q.	34.0	46.2	23.0	68
2 per cent Nickel-Moly.	900/950° C.	860° C. O.Q.	760° C. O.Q.	37.0	49.0	22.0	62
3 per cent Nickel-Chrome	900/950° C.	860° C. O.Q.	760° C. O.Q.	44.2	57.0	21.0	53
4½ per cent Nickel-Chrome¹	880/930° C.	850° C. O.Q.	760° C. O.Q.	75.0	85.0	15.0	32

¹ Treated in Test Piece size (½64" dia.).

the case-hardening treatment should not appreciably affect the properties of the core, and, for a given type of steel, the lower the carbon content the higher is the critical range on heating and the less is the steel affected by the case-hardening treatment. Secondly, the core must be tough with a single quench treatment without tempering, and this can only be obtained from low carbon steels. Hence from a plain carbon case-hardening steel the maximum tensile strength obtainable in the core is about 35 tons per square inch after water quenching. The actual value will, of course, depend on the size of the section treated, and where this is very small a core strength of 40 tons per square inch may be obtained. In heavy work where a higher strength is desired, the nickel or nickel-chromium alloy steels are used. A list of these steels along with their mechanical properties after treatment is given in Table XX, from which it will be seen that they offer high strength combined with excellent toughness. Besides their superiority in this respect, the alloy case-hardening steels have further very important advantages. In the plain carbon steel, trouble is often experienced owing to distortion which may accompany the water-quenching operations, especially from the higher temperature. With alloy steels, on the other hand, the desired properties may be obtained by oil quenching, thus reducing distortion to a great extent. Compared with plain carbon steels under the same carburizing conditions, the alloy steels absorb carbon at a lower rate, and they are therefore less liable to contain excess cementite; consequently "flaking" of the case is less frequent.

Testing Case-hardened Steels

The properties of the core (tensile strength and toughness) are determined from a sample bar of the material, which is subjected to the specified case-hardening treatment so far as temperature, time, and cooling rates are concerned, but without the formation of the case. To save time it is convenient to omit the preliminary long soaking at the carburizing temperature (blank carburizing), since this has practically no effect on the mechanical properties of the core, provided it receives the subsequent refining and hardening treatments. The toughness is of course estimated by the impact test.

The hardness of the case may be tested by the Vickers Diamond Hardness Tester or by the Scleroscope. The H_n number

should be from 780 to 830. For the reasons stated above, such hardness tests should be supplemented by micro-examination of a sample test piece. Fig. 85 shows the fracture test of a case-hardened sample. It will be observed that the case has fractured without flaking, while the core is fibrous (Plate 17).

Soft Spots in Case-hardened Steels

Abnormality—the occurrence of soft spots in the case—is a familiar trouble in case-hardening practice. The cause of this is frequently to be found in irregular carburizing, the soft spots coinciding with areas which have not absorbed the requisite amount of carbon to give the necessary hardness on quenching. There are, however, certain carbon steels in which soft spots occur in spite of correct treatment. On analysis the soft areas are found to contain the normal amount of carbon, and yet they will not harden properly on quenching.

The micro-structure of abnormal steels after carburizing offers the explanation. In a normal steel, slow cooling after carburizing results in a uniformly coarse-grained structure of the case, and the cementite network of the grain boundaries is well defined. Abnormal steels, on the other hand, with the same carburizing treatment reveal a mixed grain size, some grains being of normal coarseness, while others remain fine (fig. 89). Now, to quote from page 64 *ante*, “increasing the grain size lowers the critical cooling rate in the same way as do alloy additions”. Thus the critical cooling rate of the fine-grained portions of the case of an abnormal steel is faster than normal, and insufficient quenching (arising from steam bubbles, for example) may result in the formation of soft spots. Abnormal steels may often be successfully treated by employing a more drastic quench, such as a brine solution.

Abnormality in steel is caused by the use of small quantities of aluminium as an additional deoxidizer. If added in sufficient quantity, it renders the steel fine-grained throughout, and by controlling the addition of aluminium to the ladle and/or the mould, “grain-controlled” steels are manufactured.

Measurement of Grain Size

The above explanation of abnormality is not complete, for one would expect that the coarse grain of the normal carburized steel and the mixed grain of the abnormal carburized

steel would be equally refined by the subsequent case-hardening treatment. This is not so. While it is true that after this treatment the difference in grain size is not so marked, a coarse-grained structure as revealed by the carburizing test is an indication of more or less rapid grain growth immediately the critical range is reached, and conversely a fine-grained structure as revealed by the carburizing test is an indication that no appreciable grain growth will occur below the carburizing temperature. Thus the tendency to grain growth or otherwise is shown by the carburizing test described below. This test is known as the McQuaid-Ehn carburizing test, after the U.S.A. metallurgists who first suggested its use for this purpose, and the grain size revealed by it is known as the McQuaid-Ehn grain size. The test is carried out under standard conditions, viz. 925° C. for 6/8 hours. The grain size number is determined by comparing the microscopic image at 100 diameters magnification with a standard grain size chart. Examples of different grain sizes are shown in figs. 86 to 89 (Plate 19). The expression "fine-grained steel" refers to steel with a grain size number of 6 or higher.

It should be clearly understood that the McQuaid-Ehn grain size is not the same as the "austenitic" grain size, which is the size of the austenite grains at the moment of quenching. For alloy steels in particular it is usually very difficult to determine the austenitic grain size, and for most purposes the McQuaid-Ehn grain size provides all the information required.

Coarse-grained steels have the advantage that, as shown above, they respond more readily to quenching, i.e. they are deeper hardening. They have also in general better machining properties than fine-grained steels. On the other hand, fine-grained steels have less tendency to distort on quenching, and since the core refining treatment also hardens the case while retaining fine grain, no further treatment is required. Fine-grained steels exhibit better notch toughness, and are preferable for applications where resistance to shock is necessary.

Gas Carburizing

The essential difference between pack carburizing and gas carburizing is that in the latter process the gases are generated outside the carburizing box or container. The carburizing

McQuaid-Ehn Grain Sizes

PLATE 19

No. 5/7

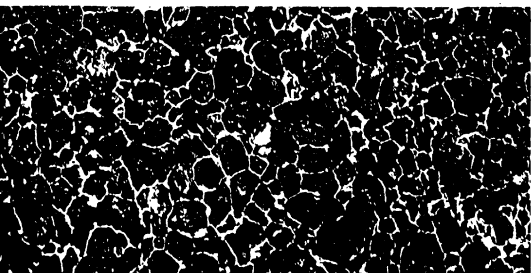


Fig. 86

No. 3/4

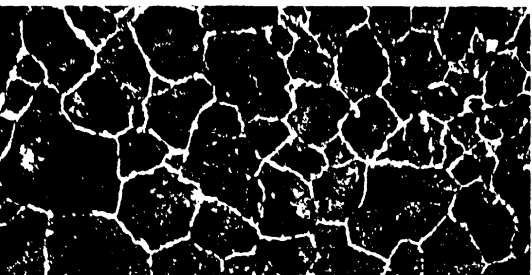


Fig. 87

No. 1/2

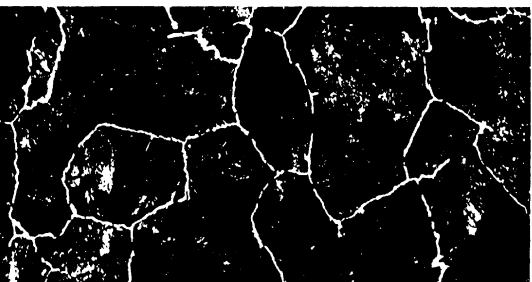


Fig. 88

Mixed 1/2 and 6/8

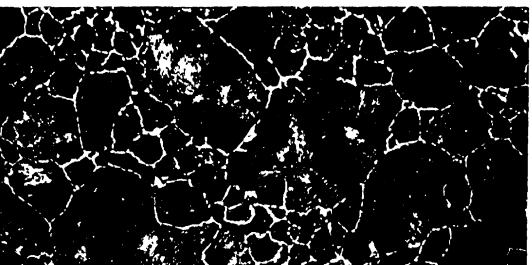


Fig. 89

X 100

gases are chiefly carbon monoxide and methane, and town's gas has been successfully employed for the purpose. It is essential, however, that the gas should be freed from moisture, oxygen and carbon dioxide. Gas carburizing has several advantages over pack carburizing, in that with a properly distributed gas flow through the container, more uniform carburizing is obtained. Also, by controlling the gas flow, the depth of case can be more accurately controlled. Rapid carburization may be allowed, since, although the carbon concentration may rise to 1.4 per cent in the case, this can be reduced to any desired value by stopping the gas flow and continuing the soaking at the carburizing temperature. This soaking or equalization period results in a more gradual change in composition from case to core than is normally obtained with pack carburizing. The subsequent heat treatment of the carburized articles is the same as that for pack carburizing.

It should be remarked that after passing through the carburizing box the gases are still, of course, available as fuel.

Cyaniding

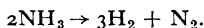
The cyanide treatment is a rapid and economical method of obtaining a hard, shallow case. The articles are dipped in a bath of molten sodium cyanide, diluted as may be required with sodium carbonate, at about 900° C. for one to three hours to give a case depth of .01/.02 in. with a carbon content in the case amounting to about 0.6 per cent. Direct quenching from the cyanide bath is sufficient to refine the core and harden the case. The cyanide treatment gives a case hardness somewhat higher than that obtained by the carburizing treatment. This is due to the adsorption of nitrogen as well as carbon, the nitrogen being obtained from the decomposition of the sodium cyanide:



Nitriding

In the case-hardening processes just described, the steel is first carburized and then heat-treated. In the nitriding process, however, the steel is first quenched and tempered to give the required mechanical properties and is then heated to approximately 500° C. in an atmosphere of ammonia. At this

temperature about 30 per cent of the ammonia dissociates and the nitrogen thus formed is adsorbed by the surface of the steel, which becomes intensely hard without further treatment.



Only "nascent" nitrogen is active, so that a steady flow of ammonia is necessary to maintain the supply of active gas. The process is slow, about 30/70 hours being required to give a case depth of 0.015 in.

The success of the process depends upon the formation of stable nitrides precipitating in the iron lattice. Aluminium and chromium form such nitrides, so that special steels are necessary for satisfactory results. Two standard steels have the composition and properties shown.

C	Mn	Ni	Cr	Mo	Al	V
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
B.S. En. 40B						
0.20—	0.40—	0.40	2.90—	0.40—	—	0.25
0.30	0.65	max.	3.50	0.70	—	max.
B.S. En. 41.						
0.18—	0.65	0.40	1.40—	0.10—	0.90—	
0.45	max.	max.	1.80	0.25	1.30	
Mechanical Properties.						
	U.T.S.		Y.P.	El.	Izod.	
	Tons/sq. in.		Tons/sq. in.	Per cent.	Ft.-lbs.	
			Min.	Min.	Min.	
B.S. En. 40	45-70 min.		34-48	22-17	40-35	
B.S. En. 41	35-65		24-42	24-17	45-35	

En. 41 gives a case of exceptional hardness ($H_D = 1100$) but has not the same depth-hardening properties as En. 40, the case-hardness of which ($H_D = 800/900$) is sufficient for most purposes.

The best properties in the nitrided case are obtained when the steel possesses a uniformly sorbitic structure, so that efficient heat treatment is of paramount importance. Decarburization must also be absent, and finish machining is therefore done after heat treatment. Although the tempering temperature is always above the nitriding temperatures, it is usual to give the steel a stabilizing treatment of 500–550° C. for 4/5 hours to avoid distortion during the prolonged nitriding treatment.

The surfaces to be nitrided must be clean to ensure efficient adsorption, and the parts not to be hardened are protected by plating with tin.

The maximum hardness of the case is developed about $\cdot001/\cdot002$ in. below the surface and this amount is ground off the surface after nitriding. Fig. 90 shows the structure of nitrided steel (Plate 18).

As can be readily understood, the nitriding process is an expensive one and is therefore limited to important parts of machinery, particularly aero-engines. Cylinder liners, crankshafts, valve-stems, spindles, links, and other items required to withstand abrasion or fatigue are common examples.

The chief advantages of nitrided steels are these:

1. They give a harder case than can be obtained with carburizing.
2. The hardness of the case is retained up to $450^{\circ}\text{C}.$, while carburized cases soften appreciably above $150^{\circ}\text{C}.$
3. The process leaves the steel free from internal stresses arising from heat treatment.

Flame Hardening

This process consists simply in using a suitable gas flame to heat the surface to be hardened above the critical point and cooling rapidly. Any steel which can be hardened by quenching may be used, but suitable precautions are necessary to avoid an abrupt transition from the hard face to the softer core, otherwise spalling or flaking will result. The time required depends upon the intensity of the heat applied at the surface and the depth of case required. Small surfaces, such as hammer heads, will give a case depth of $1\frac{1}{2}$ mm. in less than two minutes. The maximum hardness obtainable depends, of course, upon the composition of the steel, but excessive hardness is not desirable, since it is accompanied by excessive brittleness. This process is applied to hardening gears, cams, &c., and hand tools.

Induction Hardening

This is the same in principle as flame hardening, but the heating is much faster, a few seconds being sufficient. It consists in making the steel the core of a high-frequency sole-

noid, whereby the surface only is heated by the eddy currents set up. The very rapidity of the process demands that the steel be in a fit condition to start with. If the carbides are massive in form the time above the critical point is insufficient to dissolve them completely, and insufficient hardening will result. The previous heat treatment should be such as will produce a fine sorbitic structure so that full solution of the carbides will be rapid immediately the critical point is reached.

Fatigue Strength of Surface-hardened Steel

Reference has already been made to the improvement in the fatigue range which can be brought about by increasing the surface hardness of steel. Cold work, by shot blasting for example, or case hardening by any of the foregoing processes is beneficial. In this respect, however, nitriding is the most pronounced in its effect, owing to the compression stresses developed in the nitrided case. An excellent survey on the influence of nitriding on the fatigue strength is given by Bardgett in *Metal Treatment* (Summer, 1943). Table XXI taken from this paper summarises the results of Wöhler rotating cantilever fatigue tests on a $\frac{3}{4}$ -in. dia. bar of En. 40 steel heat treated to 67/70 tons per square inch. The nitriding treatment (72 hours at 480° C.) gave a case hardness of H_D 920/935, and a case depth of 0.014 in.

The results show that nitriding raises the limiting fatigue stress of the plain specimens by 36 per cent, and of the notched specimens by 300 per cent. The notch sensitivity is enormously reduced by nitriding.

Un-notched specimens from the same type of steel were prepared with different fillet radii and the test results (Table XXII) again show well the beneficial effects of nitriding.

TABLE XXI
SUMMARY OF FATIGUE TEST RESULTS ON 67-70 TONS PER SQUARE INCH MATERIAL

Condition of test specimens	Un-nitrided		Nitrided	
	Plain (P)	Notched (N)	Plain (P)	Notched (N)
Type of specimen				
Max. stress (M.S.), tons per square inch	67.9		70.0	
Limiting fatigue stress (L.F.S.), ± tons per square inch ..	38.25	12.5	52.0	50.25
$\frac{L.F.S.}{M.S.}$	0.56	0.18	0.74	0.72
Notch sensitivity— $\frac{L.F.S.(P) - L.F.S.(N)}{L.F.S.(P)}$..	0.67		0.03	

TABLE XXII
FATIGUE TEST RESULTS SHOWING EFFECT OF NITRIDING ON NOTCH SENSITIVITY IN FATIGUE

Fillet radius (in.)	3	$\frac{1}{4}$	$\frac{1}{8}$	As small as possible.
Limiting fatigue stress ± tons per square inch (Un-nitrided)	35.4	31.2	26.8	11.0
Limiting fatigue stress ± tons per square inch (Nitrided)	45.2	45.2	43.0	34.5

CHAPTER X

The Cold Working of Steel

That steel is capable of undergoing considerable plastic deformation in the cold, is evident from its behaviour under a tensile or bend test. This property is utilized in many ways by the engineer, for example in the rolling of thin sheets, the drawing of tubes and wires, and the flanging and pressing of rolled plates. Cold rolling and drawing operations are invariably preceded by a pickling process to remove mill or furnace scale, which would otherwise be rolled or pressed into the steel. The material is then drawn through hard rolls or dies, and by a number of passes is reduced to the required thickness or section. It may be mentioned that, except for small sizes, the shape of the section is not altered by cold rolling. Hexagons are cold drawn from hexagons, and rounds from rounds. This procedure is adopted to ensure, as far as possible, the equalization of cold work throughout the section. Cold work has a pronounced effect on the mechanical properties and structure of steel. The tensile strength is progressively increased, the elongation, reduction of area, and Izod impact values are lowered, while the crystal grains are elongated considerably in the direction of rolling or drawing. They may even be distorted by excessive working, and particles of the hard cementite, being brittle, may be broken into fragments.

Figs. 91 and 92, Plate 20, illustrate the structure of a broken tensile test and the sheared edge of a boiler plate, respectively. The structure of cold-drawn iron wire is shown in fig. 20, and was referred to in Chap. II, p. 21. From these examples it will be observed that the structure of cold-worked steel depends upon the method as well as the degree of cold working.

The hardening of steel by cold working is due to the material being put in a state of severe strain. It will be remembered that the hardening of steel by quenching was explained as arising from a similar cause, p. 53. Although the strains are due to external influences in the one case and internal in

the other, there are many points of resemblance between work-hardened and quench-hardened steels. The changes in mechanical properties are of the same order if not degree, and reheating has similar effects on both steels.

From the foregoing considerations it is apparent that there is a limit to the amount of cold work which steel can undergo without failure. This limit depends on a number of factors, such as:

1. Chemical Composition.
2. Methods of Cold Working.
3. Micro-structure.

With regard to (1), in general, the purer the metal the more drastic cold working will it withstand.

With regard to (2) and (3) it has been shown that the structure of cold-worked steel depends on the method of working. It is obvious, therefore, that a tensile test will not indicate the cold-drawing capacity of a steel rod, but merely shows the limit of cold working by direct tension. Furthermore, the maximum amount of cold drawing which a bar of steel will undergo depends upon the amount of reduction of area at each pass. What this should be, to obtain the maximum effect, depends upon the previous history and the structure of the steel. The structure may be modified by suitable heat treatment. Thus the art of cold-working metals includes the art of heat-treating, so that by skilful arrangement of the various stages of cold work a first-class product may be obtained. Material which has to undergo considerable reduction of area may be worked in several stages, being annealed after a few passes, repickled if necessary, cold worked in a further series of passes, reannealed, and so on. The annealing treatment is carried out in various ways. Spheroidizing (see p. 52) is sometimes adopted.

As might be expected, a steel with a spheroidized structure is able to undergo considerable cold work, provided the carbon content is not too high. Such steel, however, has a very low elastic limit, and is not very suitable for service. For this reason it is usual to normalize the steel after working to restore the pearlite or sorbite structure. A most valuable preliminary treatment carried out on medium and high carbon hypoeutectoid steel rods, before drawing into wire, is known as "patenting". This is a continuous process whereby the rods



Fig. 91.—Fractured Tensile Test.
× 180



Fig. 92.—Sheared Edge of Boiler
Plate. × 180

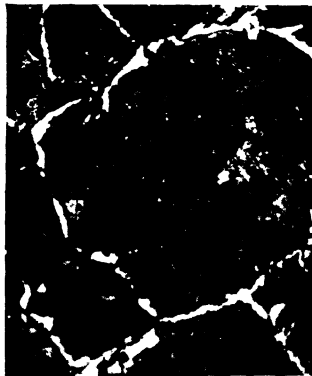


Fig. 93.—Patented Steel (C. .5 per
cent). × 250

TABLE XXIII¹
THE COLD WORKING OF ANNEALED AND OF PATENTED STEELS

Treatment and Structure.		Original Diameter. In.	Final Diameter. In.	Maximum Stress. Tons per sq. in.	Elong. Per cent on 2 in.	Reduction of Area. Per cent.	Reduction by Cold Working. Per cent.
Carbon = 0.5 Silicon = 0.13 Manganese = 0.05 Sulphur = 0.037 Phosphorus = 0.039	{ Annealed, 60 per cent pearlite, 40 per cent ferrite.	1.25	0.833	66	7.5	1	57
		Limit of drawing; bar broke at this point.					
	{ Patented, 90 per cent sorbite, 10 per cent ferrite.	1.25	0.575	92.8	7	12	79
		Bar not fractured; die would not stand further reduction.					
Carbon = 0.85 Silicon = 0.12 Manganese = 0.30 Sulphur = 0.022 Phosphorus = 0.020	{ Annealed, laminated pearlite.	0.16	0.127	60	—	Nil.	37
		Limit of drawing; wire broke at this point.					
	{ Patented, sorbite.	0.16	0.053	148	—	28	89
		Wire not fractured; could have been drawn further.					

A. T. Adam, *Wire Drawing and the Cold Working of Steel* (H. F. and G. Witherby).

are drawn through a furnace so that they are slowly heated to about 1000°C ., and cooled in air or molten lead at a moderately fast rate.

The structure of patented steel (fig. 93, Plate 20) presents three distinctive features. First, the high temperature results in the formation of large crystal grains. Second, the rate of cooling to 800°C . permits of the deposition of some of the ferrite as an envelope round the grain boundaries. Third, the relatively rapid cooling through the lower critical point gives rise to the formation of sorbite, in which the cementite exists in very small particles. These three structural features combined result in a material which is particularly adapted for undergoing severe cold work. This is well illustrated by Table XXIII, which compares the capacity for cold work of annealed and patented steels both in bars and in the form of wire.

Except for the finer sizes of wire, the rods require to be patented once only, being sufficiently ductile in this condition to withstand reductions of area up to 90 per cent in some cases.

The Heat Treatment of Cold-worked Steels

The effect on the mechanical properties of reheating cold-worked steels is shown in Tables XXIV and XXV. It will be seen that the yield point and the tensile strength are raised slightly while there is a marked increase in the limit of proportionality. At the same time, there is a decrease in the ductility and toughness. These changes are evident up to about 450°C . (Heating cold-worked steels within the region of 250° to 450°C . is commonly called "blueing".) Further heating results in a slight softening of the steel, and at 520°C . there is a sudden softening of steels with low carbon content. This is due to the recrystallization of the strained ferrite, which now forms normal equiaxial crystals (fig. 16). The pearlite areas are not affected at this temperature, so that the higher carbon steels do not show this sudden change of properties.

At temperatures above 600°C . the pearlite or cementite commences to spheroidize, and this change is rapid in cold-worked steels. As already stated, this results in further softening of the steel, and leaves it in a condition unsuitable for service. Such steel should therefore be normalized, to restore the pearlitic or sorbitic condition of the cementite.

The heat treatment, if any, to be given to cold-worked steels



Fig. 94.—Cold-worked Steel (C .10 per cent), heated to 720° C. $\times 5\frac{1}{2}$

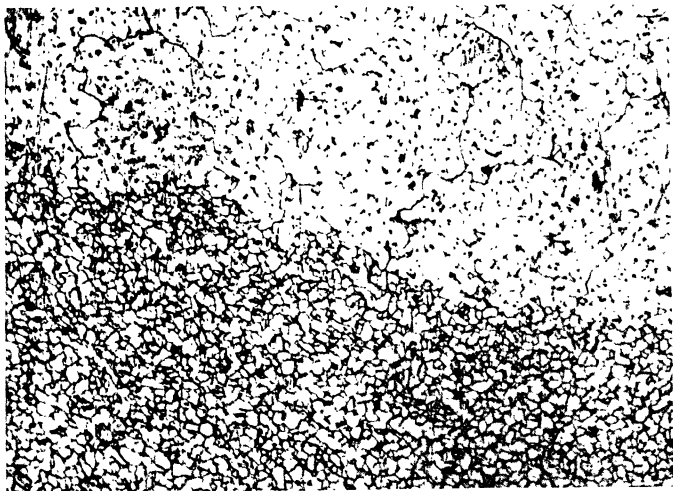


Fig. 94a.—Cold-worked Steel (C .10 per cent), heated to 700° C. $\times 55$

TABLE XXIV
THE MECHANICAL PROPERTIES OF REHEATED COLD-WORKED STEELS

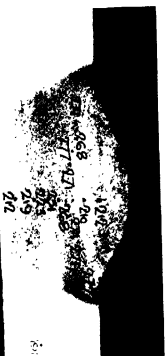
Reheating Temperature, °C.	Carbon. Per cent.	Manganese. Per cent.		Yield Point, Tons per sq. in.	Limit of Proportionality, Tons per sq. in.	Maximum Stress, Tons per sq. i n.	Elongation Per cent on 2 in.	Reduction of Area, Per cent.	Impact. Ft.-lbs.
	·1	·4	·02						
—	16	32	56	6	22	10			
100	18	33	56	6	21	8			
200	20	31	54	8	24	7			
300	22	30	52	8	25	7			
400	25	29	50	10	27	9			
500	24	26	46	12	30	10			
530	16	19	29	24	56	96			
600	12	16	25	28	60	70			
Normalized									
920	14	18	25	30	64	95			

TABLE XXV
THE MECHANICAL PROPERTIES OF REHEATED COLD-WORKED STEELS

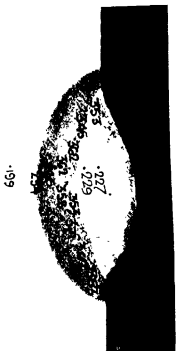
Reheating Temperature, °C.	Carbon. Per cent. ·52	Limit of Proportionality, Tons per sq. in.	Yield Point, Tons per sq. in.	Manganese. Per cent. ·54	Maximum Stress, Tons per sq. in.	Elongation Per cent on 2 in.	Reduction of Area, Per cent. ·04	Silicon. Per cent.	Impact. Ft.-lbs.
—		27	51		70	5	18		8
100		28	51		71	5	18		5
200		37	53		75	4	17		4
300		44	54		74	4	16		4
400		52	54		71	5	20		9
500		42	45		62	10	34		16
600		33	39		49	16	45		26
670		20	24		40	26	60		45
Normalized									
840		24	29		45	18	46		25

PLATE 22

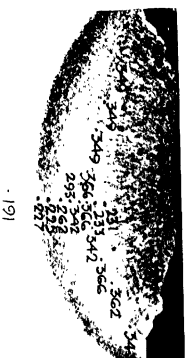
$\frac{1}{4}$ in. plate



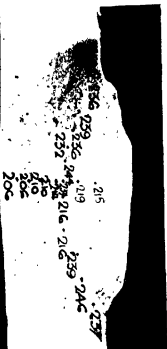
$\frac{1}{2}$ in. plate



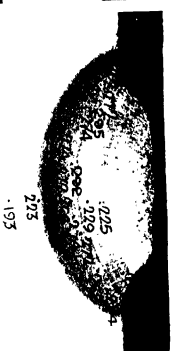
1 in. plate



$\frac{1}{4}$ in. dia.
electrodes



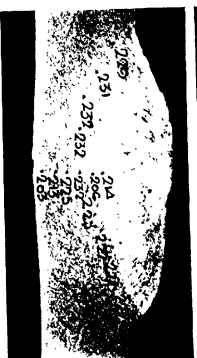
$\frac{1}{2}$ in. plate



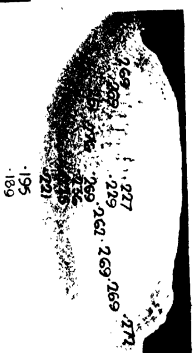
1 in. plate



electrodes
7/8 in. dia.



$\frac{1}{2}$ in. plate



1 in. plate

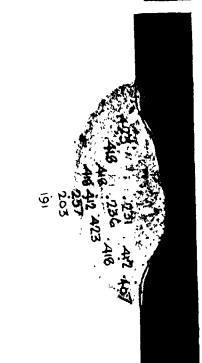


Fig. 100. N_3
Effect of Plate Thickness and Electrode Size
($p, 1.75$)

depends upon the purpose for which the material is required, and on the tensile strength desired. If good elastic qualities are essential, blueing is necessary. On the other hand, if toughness is an important consideration, a short-time heating to 500°/600° C. is advisable, or if a high tensile strength is not necessary, the material may be normalized.

It should be noted that cold rolling and drawing operations are performed on steel for one or more of the following three reasons:

1. Because it is the most economical method, or the only method, of manufacture. For example, very thin sheets could not be rolled hot because they could not retain sufficient heat, and scaling would be excessive in proportion to the thickness.

2. To increase the tensile strength. This applies particularly to high-tensile wire, which, after patenting and drawing, may have a tensile strength approaching 200 tons per square inch.

3. To enable bars and sheets to be finished to more exact dimensions. For this reason bars for machining in automatic lathes are usually cold drawn or bright turned. Bars for such purposes are hot rolled to $\frac{1}{16}$ in. diameter over-size, and then cold drawn to the required dimensions. The reduction of area produced by cold work thus depends on the size of the rolled bar, being relatively large for a $\frac{1}{2}$ -in. diameter bar, and small for a 2-in. diameter bar, so that the smaller bar would have its tenacity increased more than would the bar of heavier section. To make allowance for this variation, the carbon content of a bright-drawn bar should for a given tensile strength

TABLE XXVI

THE COMBINED EFFECT OF CARBON AND COLD DRAWING ON
THE MECHANICAL PROPERTIES OF STEEL

Carbon. Per cent.	Diameter of Bars. As rolled. In.	Bars. Drawn. In.	Reduction of Area by Drawing. Per cent.	Maximum Stress. Tons per sq. in.	Elong. Per cent.	Reduction of Area. Per cent.
·15	$\frac{5}{16}$	$\frac{1}{4}$	36	41·0	12	34
·23	$\frac{9}{16}$	$\frac{1}{2}$	21	39·4	15	41
·29	$\frac{13}{16}$	$\frac{3}{4}$	15	41·0	17	43
·33	$1\frac{1}{16}$	1	11	40·6	19	46
·36	$1\frac{9}{16}$	$1\frac{1}{2}$	8	40·2	22	49
·38	$2\frac{1}{16}$	2	6	40·0	24	51

vary according to the size of the bar. This is illustrated in Table XXVI, from which it will be noted that the ductility of the more severely drawn bars is inferior. This shows that it is not good practice to raise the tenacity of bars for general engineering purposes by excessive cold work.

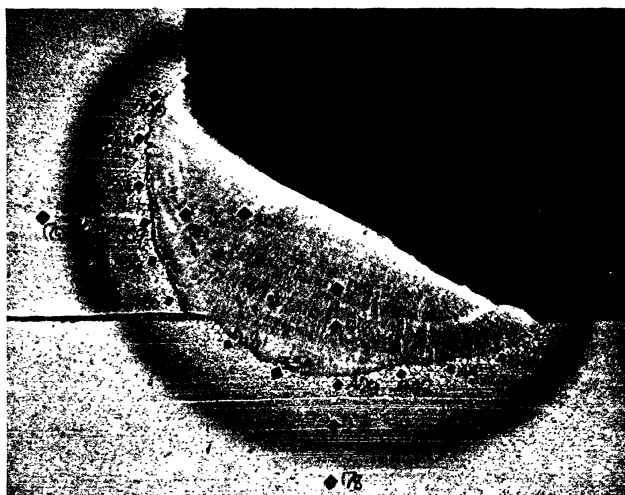
Two phenomena which appear under certain conditions when iron or mild steel is heated after cold working are of special importance. They are:

- (1) Grain Growth.
- (2) Strain Ageing.

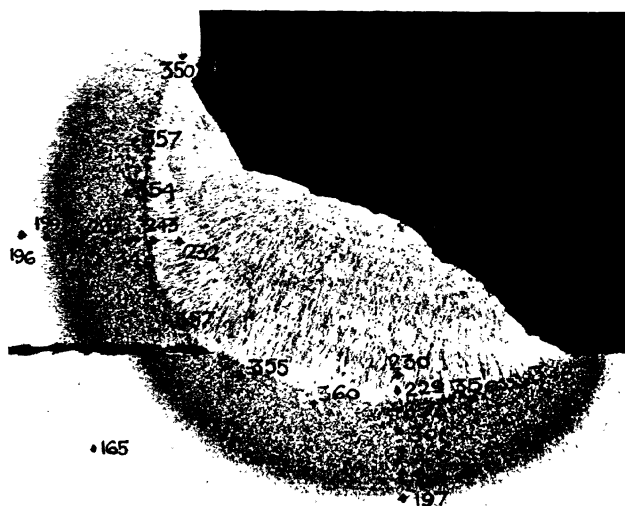
(1) *Grain Growth*.—The recrystallization of ferrite which takes place when cold-worked iron or steel is heated to 520°C . produces a refinement in the structure which, on further heating, is followed by grain growth. When the cold work has been slight in extent, recrystallization is not complete, and excessive grain growth does not follow. Also, if the cold work has been considerable, recrystallization begins at many centres throughout the material, resulting in a very fine structure, which is not appreciably coarsened by further heating.

Between these extremes of light and heavy cold work, however, there is a range of cold work which results in excessive grain growth at $600^{\circ}/800^{\circ}\text{C}$., following upon the recrystallization at 520°C . This may be conveniently demonstrated by making a Brinell hardness impression on a sample of mild steel, and then reheating the sample to 700°C . for one hour. A section below the Brinell impression, when polished and etched, reveals the structure shown in fig. 94. The severely cold-worked portion immediately below the impression has a very fine structure, while below that again there is a zone of very large crystals. This is the part which has received the critical amount of cold work (Plate 21).

The critical range of cold work is invariably exceeded in the drawing of wires, but may just be attained in the bright-drawing of bars for machining, and in other forms of cold work. Iron or steel containing less than .18 per cent carbon, which has been cold-worked within the limit of about 8 per cent to 20 per cent reduction of area, should therefore never be softened between 580°C . and 800°C . Such material may safely be heated to 550°C . only, or fully annealed or normalized from $900^{\circ}/920^{\circ}\text{C}$.



B.S.S.
548



B.S.S.
968

Fig. 102.—Fillet Welds. $\times 6$

(p. 138)

(2) *Strain Ageing of Mild Steel.*—The impact value of mild steel is not seriously lowered by cold work, unless the reduction of area reaches 20 per cent. But if slightly cold-worked steel is reheated after cold working the impact value falls considerably, showing that this treatment has produced brittleness.

TABLE XXVII

IZOD IMPACT TESTS ON DEAD SOFT STEEL

Carbon. Per cent.	Manganese. Per cent.			Silicon. Per cent.
·14	·60			·03
Reheating Temperature after Stretching, °C.	Stretched 10 per cent before treatment. Izod Impact Values, ft.-lbs.			
	1	2	3	Average.
Nil.	70	71	74	71·7
100	28	28	73	43·0
200	30	24	74	42·7
250	11	12	9	10·7
300	8	30	15	17·7
350	87	96	88	90·3

This peculiar type of brittleness, which is most marked in steels containing less than ·16 per cent carbon, is known as *ageing*. The effect of reheating temperatures on the impact value of mild steel cold worked by tension is shown in Table XXVII, while Table XXVIII shows the effect of different degrees of cold work followed by reheating to 250° C.

From these tables it appears that the maximum embrittling effect is obtained with an extension of about 15 per cent followed by reheating to 250° C. for 30 minutes. To quote

TABLE XXVIII

IZOD IMPACT TESTS ON DEAD SOFT STEEL
STRETCHED AND REHEATED TO 250° C.

Degree of Stretching. Per cent.	Izod Impact Values, ft.-lbs.				Average.
	1	2	3	4	
Nil.	85·0	93·0	87·0	86·0	87·75
5	67·0	72·5	87·5	23·0	62·5
10	13·5	25·0	11·0	11·5	15·25
15	6·0	9·0	9·0	8·0	8·0
20	10·0	7·0	9·0	9·0	8·8

from the paper from which these tables have been taken:¹ "The results given are of vital interest in connexion with pressed articles, particularly if reheated after pressing, . . . for lifting chains, . . . for rivets, and for numerous other articles where hitherto the ductility of dead soft steel has not been questioned."

The importance of the subject is such that considerable research has been and is being done on this question. It has been found that only certain steels are subject to this embrittling effect, but the underlying causes of this phenomenon are not yet known. It has also been shown that steels which are otherwise susceptible are made immune from this type of brittleness, if they are quenched and tempered before being cold-worked.

Deep Drawing and Pressing

This is a form of cold work which is performed on thin sheets whereby they are pressed in dies to various shapes, such as motor-car bodies, oil sumps, and cartridge cases. The degree of cold work may be slight or very severe, and may be carried out in one or more operations, as in bright drawing. In general the sheets are supplied in the softest possible condition and preferably with a spheroidized structure. Only very low carbon steels and certain austenitic steels are able to withstand severe deep drawing. The surface of the sheets must be as smooth as possible, and pickling is therefore necessary. Inclusions, especially of the silicate type, are most harmful, particularly when near the surface. It is for this reason that rimming steel is frequently employed. Rimming steel is steel which has been cast in a "non-killed" state (p. 33), with the result that as the ingot solidifies there is constant evolution of gas (hence the term "effervescing" sometimes used to describe this steel). This effervescing action has the effect of concentrating the carbon and the impurities towards the centre of the ingot, the outside rim being very nearly pure iron. This is illustrated in fig. 108, Plate 27, which is a sulphur print from the cross section of a rimmed steel billet. Very clean and smooth surfaces are obtained when ingots of rimmed steel are rolled into sheets.

¹ G. R. Bolsover, *Journal of the Iron and Steel Institute*, 1929, I, pp. 473 *et seq.*

Steels of the austenitic type are particularly adapted to severe deep-drawing operations, owing to their high ductility.

One of the problems of deep pressing steel is that of strain ageing; it has been found that a fully-killed steel deoxidized with aluminium and titanium is particularly free from strain age embrittlement.

CHAPTER XI

High-Temperature Testing of Steel¹

In Chapter I it was stated that while the rate of strain does not appreciably affect the results obtained in tensile testing at ordinary temperatures, at higher temperatures it is of paramount importance. The effect of different rates of strain on the tensile strength at different temperatures is shown in fig. 95. It will be noted that with increasing temperature the maximum stress decreases slightly, but above 150° F. there is an increase in strength which reaches a maximum and then falls away rapidly. The lower the rate of straining the lower is the temperature of maximum increase in tensile strength and the higher is the maximum tensile stress obtained. Above approximately 450° F., the lower the rate of strain the lower is the maximum tensile strength. These phenomena are due to the simultaneous effects of time and temperature which result in straining, ageing, and then softening of the strain hardened material. In blueing on the other hand the steel is first strained and then aged. In high temperature tensile testing the degree of hardening, and the amount of softening depend upon the temperature and the time, a long time at low temperatures being equivalent to a short time at high temperatures. Below 450° F. the softening effect is negligible. Similarly, the effect of temperatures above 450° F. is to soften the material, longer times at lower temperatures being again equivalent to shorter times at higher temperatures. Tensile testing of steel above 150° F. may be considered as simultaneous cold working, ageing, and, in the higher range of temperatures, softening. For example,

¹ In this chapter temperatures are shown in °F. in accordance with current engineering practice.

in Curve 2 (fig. 95) the maximum occurs about 300° F., because the time taken to carry out the test coincides with the time required to cause the maximum amount of ageing at that temperature. At lower temperatures the time is not sufficient and the test breaks before maximum strain ageing is obtained, and in consequence the maximum stress is lower. At higher temperatures maximum strain ageing is reached during the test and a certain amount of softening takes place before the test breaks.

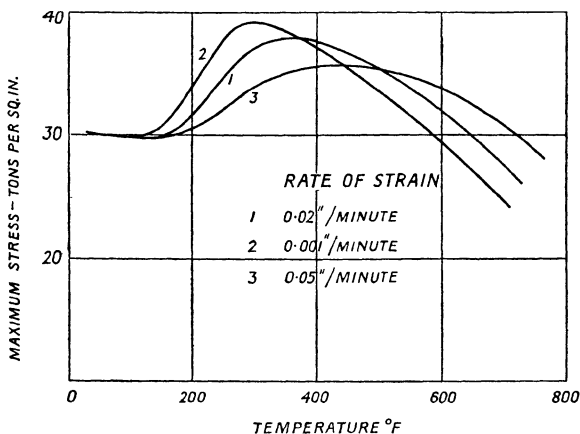


Fig. 95

Above about 450° F. the time effect becomes increasingly important, i.e. a very slow rate of straining results in increased softening, and consequently a much lower ultimate tensile stress than is obtained by a rapid rate of straining. Thus at high temperatures the application of a constant stress may result in slow continued strain until fracture. This phenomenon is known as "creep". The greater the stress and the higher the temperature, the greater will be the rate of strain and the sooner will fracture occur.

Fig. 96 shows the relationship between temperature, stress and time to fracture of a medium carbon steel. If, during the course of a tensile test at constant stress, the elongation of the test piece with time is measured by means of a suitable

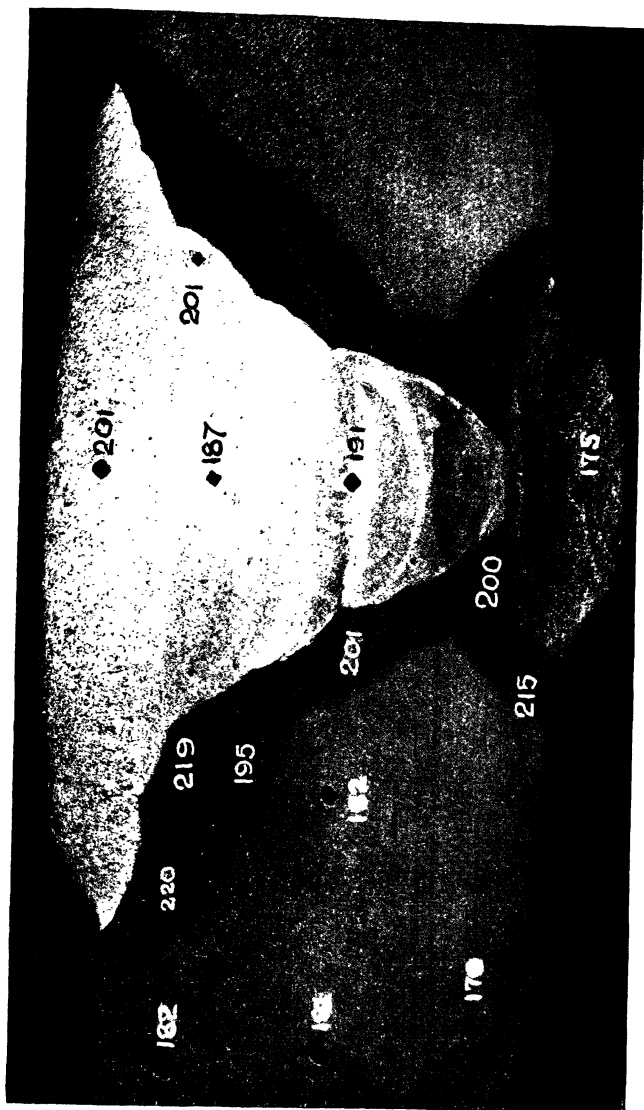


Fig. 103.—Multi-run Butt Weld. $\times 6$
(p. 138)

extensometer, a "creep curve" is obtained. In long-time creep testing, however, it is not practicable to continue the test until fracture takes place, nor would this information be of much value, since in the great majority of applications it is necessary not only that the metal should not break under stress but also that the amount of deformation during the

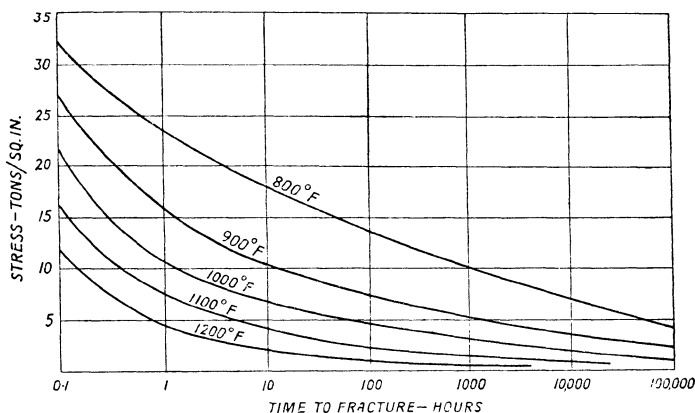


Fig. 96

working life should be limited to an amount depending upon the design. For example, the permissible deformation for some classes of turbine work may be 0.1 per cent or even less during a period of from 10 to 20 years, whereas for boiler and superheater plant a deformation of 0.5 per cent or more may be allowed.

Creep Test

A creep test may be defined as a test in which is measured the amount of deformation with time at a constant stress. The duration of the test may or may not be sufficient to cause rupture. In steel, creep is not measurable below 450° F. and does not become serious until about 700° F. Under working conditions creep may occur under tensile, compressive or torsional stresses, but the investigation of creep has so far been largely confined to tensile testing. Under some conditions the stress diminishes as a result of creep; a typical

example of this is a bolt which may slacken under creep conditions. In the ordinary creep test the shape of the curves obtained is illustrated diagrammatically in fig. 97, which shows a series of curves obtained at constant temperature but with different stresses, No. 1 representing the highest and No. 7 the lowest stress.

In Curve No. 3, the first part AA consists of the elongation on loading the steel. If the stress is less than the L.P. at the temperature of test the elongation will be wholly elastic;

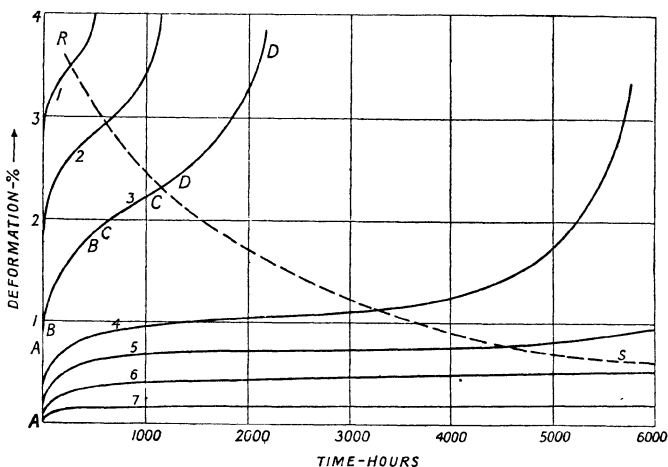


Fig. 97.—Typical Creep Curves

if greater than the L.P., some plastic strain will also take place. The next stage shows further plastic elongation with time, and in the second part BB there is a decreasing rate of elongation or creep until stage CC is reached, where the rate of creep is either constant or asymptotically approaches a constant value. The rate of elongation then begins to increase in stage DD until rupture takes place. If, however, the load is removed before rupture the test piece will contract elastically by an amount equal to the elastic elongation at the beginning of the test. A small amount of creep recovery also takes place with time on removal of the load; thus the steel possesses both elastic and plastic properties. When drawing creep

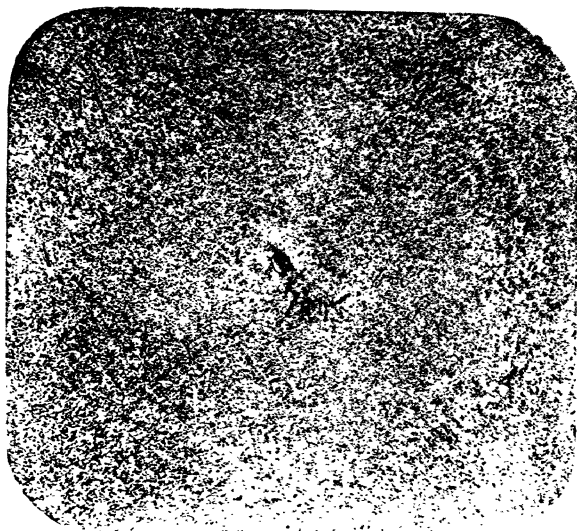


Fig. 104.—Pipe in Steel (Deep-etch Test)

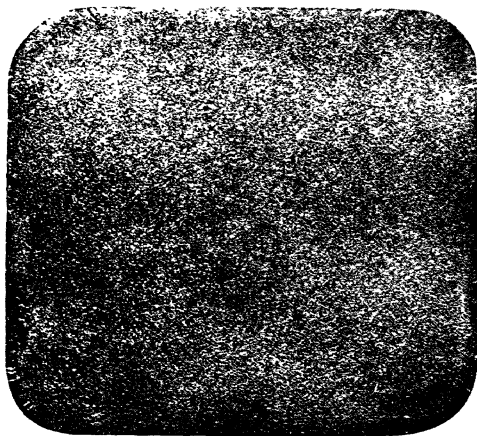


Fig. 105.—Deep-etch Test of Sound Steel
(*p. 143*)

curves it is usual to plot only the permanent plastic elongation (i.e. the creep strain) against time, omitting the elastic portion of the elongation on loading. From the completed creep curve it is thus easy to note the total amount of creep strain after any period of time. The creep rate at any time during the test is given by the slope of the tangent to the curve at that time.

The curve RS indicates the times on the different curves where the creep rate just begins to increase. Curves 6 and 7 lie below the curve RS up to 6000 hours, but at a later stage they also would show an increasing creep rate.

A simple explanation of the creep curves is similar to that given above for the high-temperature tensile test. When the load is first applied the loading and strain hardening of the different crystal grains in the steel is very irregular. In those grains most favourably orientated, the strain hardening is more intense and the rate of softening due to temperature is also greater. The initial movement is thus larger than would occur if the stress were evenly distributed over every grain. Thereafter there is a levelling up or equalization between strain hardening and the removal of strain hardening by thermal influence, and so the creep rate tends to become constant. In the last stage of the test the balance is upset and the creep rate increases. This may be due to the thinning down of the test piece resulting from increased strain, or what perhaps is of more importance, a change in the actual structure of the steel may be brought about by the prolonged exposure at the operating temperature.

Factors Influencing the Creep Strength

In itself the tensile creep test is a straightforward test involving temperature, stress and time. The various factors which influence the results obtained may be briefly summarized as follows:

(a) Technique of Testing

The creep-testing apparatus must conform to the following conditions:

1. Very accurate control of temperature over very long periods of time.

2. Very small variation of temperature along the actual test length of the specimen.
3. Accurate loading of the test-piece and suitable grips to ensure axial loading of the test-piece.
4. Accurate measurement of the creep of the test-piece.

(b) Chemical Composition

1. At the lower temperatures where creep is not the predominating feature, the strength is increased both by elements such as nickel and manganese, which largely enter into solid solution in the ferrite, and by carbide-forming elements, such as chromium and molybdenum, tungsten and vanadium.
2. At high temperatures the carbide-forming elements are still beneficial, but elements of the other type may actually be detrimental.
3. The only element which by itself confers considerable increase in creep resistance on ordinary steel is molybdenum. Certain other elements, e.g. vanadium, may be added in addition, and these, in association with molybdenum, give steels of still greater creep resistance.

(c) Grain Size and Heat Treatment

1. In creep tests at 750° F. and higher temperatures a fine-grained steel (grain size No. 6/8) may show a creep rate of from 10 to 100 times that of a coarse-grained steel (grain size No. 2/5).
2. By suitable high-temperature heat treatment the fine-grained steels may be coarsened and then usually show a creep rate similar to that of an ordinary coarse-grained steel.
3. On heat-treating steels with different coarsening temperatures to give the same grain size, it is found in some cases that the steels with the highest coarsening temperature still tend to give an inferior creep rate.
4. Normalizing at a high temperature improves creep by increasing the grain size, but may have a harmful effect on the other properties.
5. A tempering treatment is usually detrimental, owing to spheroidization, which in general decreases creep resistance.

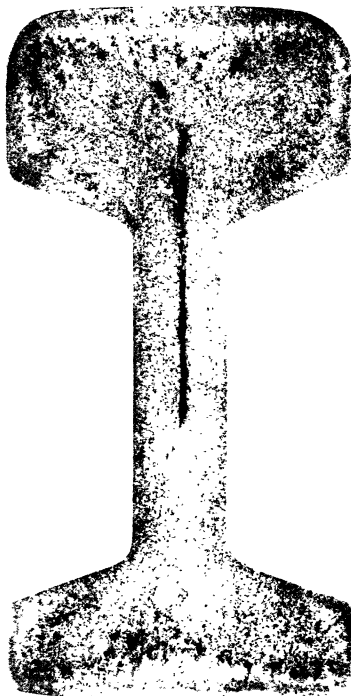


Fig. 106.—Piped Rail (Sulphur Print)

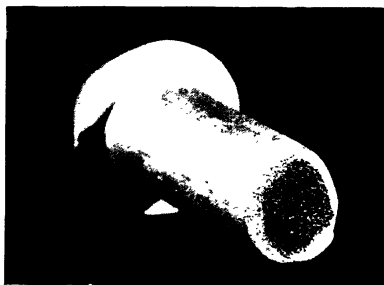


Fig. 109.—Segregation in Rivet Bar
(Deep-etch Test)

(d) Service Temperature

The degree of spheroidization is a function of temperature and time, so that service temperatures, particularly above 900° F., may have a profound effect on the structure of the steel and so cause progressively increasing creep.

(e) Effect of Workmanship

As already explained, the effect of cold working is to increase the rate of spheroidization on reheating, so that when steel is required to resist creep at high temperatures cold working should be followed by normalizing.

(f) Intercrystalline Cracking

In the ordinary tensile test at room and at high temperatures, failure takes place when the grains have elongated to their maximum extent, and the fracture is transcrystalline. Under creep conditions, when failure takes place within a relatively short time, the same type of fracture is obtained. If, however, failure occurs after a prolonged period (e.g. in low-alloy creep steels), the fracture may be intercrystalline and the elongation as low as 1 per cent. This important feature of creep behaviour may be briefly explained as follows:

The total elongation at fracture is the sum of the elongations of the crystal grains and of the "grain boundary material".¹ Failure takes place when either of these reaches its maximum value under the particular test conditions. Under short-time test conditions, the crystal grains reach their maximum elongation before the intercrystalline material, while the reverse may take place when the duration of the test exceeds a certain time. This is shown diagrammatically in fig. 98.

Curve A shows the time to fracture (i.e. time to reach maximum elongation) of the crystal grains. B is the corresponding curve for the grain boundary material. If the time to fracture exceeds time T, the fracture is intercrystalline. The amount of elongation accompanying intercrystalline failure depends upon the degree to which the crystal grains have elongated when fracture takes place, but the lower the

¹ "Grain boundary material" may or may not exist. This is a matter on which physicists are not unanimous. Elongation of "grain boundary material" here means the degree to which the distance between grains may be increased before the cohesion between them breaks down and intercrystalline failure results. The numerical value of this elongation will of course be very low.

stress the longer is the time to fracture and also the greater is the difference between the time to fracture/stress relationship of the crystal grains and "grain boundary material". Hence the longer the time required to produce intercrystalline failure the lower will be the total elongation. The effect of

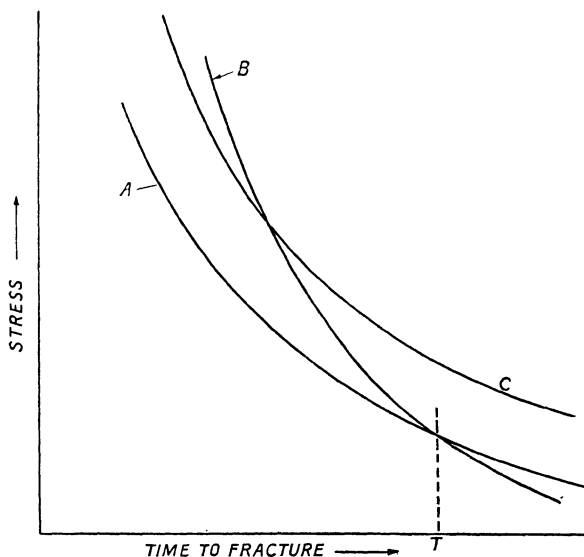


Fig. 98

low-alloy additions would appear to be to increase the strength of the crystal grains (curve C) without appreciably affecting that of the "grain boundary material". Hence, with low-alloy creep steels, intercrystalline fracture is obtained in shorter times than with plain carbon steels.

Creep Data

Exact knowledge of the creep behaviour of a steel can be obtained only by an extensive series of long-time creep tests. When this has been done it is still necessary to extrapolate the results to longer times, since the material may be required to give a life of ten years or more. A brief description of a

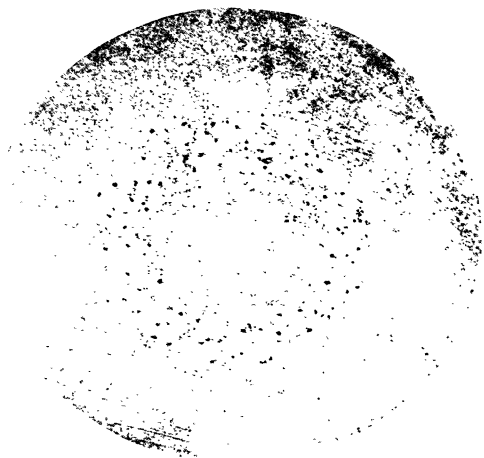


Fig. 107.—Spot Segregates (Sulphur Print)



Fig. 108.—“Rimmed” Steel (Sulphur Print)

(p. 144)

method employed by the National Physical Laboratory¹ may suffice to indicate the complexity of the problem.

A series of creep tests is carried out at different stresses and temperatures, and the time taken to give a total creep strain of 0.1 per cent is plotted against the temperature for each of

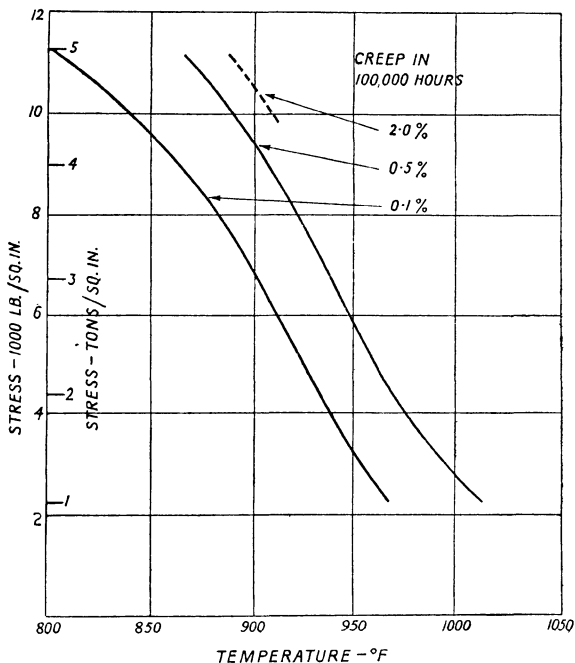


Fig. 99

the stresses employed, the time being plotted on a log scale. The curves thus obtained are extrapolated to 100,000 hours. From the values thus obtained a curve is next plotted showing the temperature/stress relationship which will give 0.1 per cent creep strain in 100,000 hours. Similar curves may be plotted for other values of total creep strain. These derived curves have the form shown in fig. 99. For example, the particular steel illustrated will give a total creep strain of

¹ *Proc. Inst. Mech. Eng.*, 1944, Vol. 151, pp. 54-62.

0.1 per cent in 100,000 hours at 905° F. under a stress of 3 tons per square inch.

It is manifestly impossible to carry out such an extensive series of tests for creep-resisting requirements with every cast of steel manufactured. Nevertheless such tests are necessary for each type of steel, to determine its mechanical properties under creep conditions. When this has been done, a short-time test may suffice to check the quality of further casts of the same type of steel made, as far as is humanly possible, under the same conditions. Many short-time tests have been proposed, and an already voluminous literature on the subject is continually growing. The important factor to consider before adopting a short-time test is the effect of service temperature and time on the structure of the steel. Where failure and not the amount of creep is the criterion of service, rupture tests (fig. 96) provide a useful relatively short-time test.

CHAPTER XII

Metallurgical Aspects of Welding and Gas Cutting

While it is beyond the scope of this book to deal at length with the subject of welding and gas cutting, it is desirable to include a brief discussion of the more significant metallurgical factors involved.

Welding

In past years when the work was carried out by the smith whose source of heat was the forge fire, welding was confined to wrought iron and very soft mild steels. Under these conditions the welding of the higher carbon steels was an exceedingly tricky business, because of the risk of burning the metal when it was heated to the very high temperature necessary to obtain proper bonding under the hammer.

With the advent of the electric metallic arc and resistance processes, the application of welding has advanced by leaps and bounds, and there are few structural shops to-day where

PLATE 28

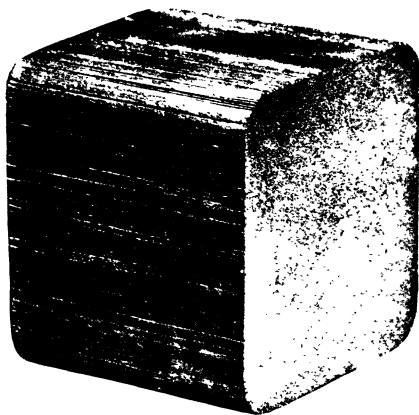


Fig. 110a. — Reeds in Steel Billet (Deep-etch Test)



Fig. 110b. — Reeds in Steel Billet (Deep-etch Test)

(p. 144)

some arc-welding machines have not been installed in place of the rival riveting hammers.

So far as the ordinary grades of structural steels are concerned (26/32 tons tensile) there are no outstanding problems in regard to the parent metal, and for these steels there is available a wide choice of electrodes which have proved themselves both in production and in service. When these steels are used for pressure vessels, it is usual to anneal the vessels at a temperature of 600/650° C. for the purpose of relieving the thermal stresses set up during welding.

In dealing with the higher carbon steels (above, say, 0.3 per cent carbon) or alloy steels, however, a problem arises from the increased hardening which occurs when they are rapidly cooled from high temperatures. In short, the property of steel which is a virtue in heat treatment, as explained in Chapter VI, is the cause of most of the troubles experienced in welding high-tensile steels, and the reason is quite simply explained. The heat generated in the arc momentarily raises the parent metal at the weld boundary to a very high temperature; then, as the electrode proceeds along the joint, cooling commences and the comparatively large mass of surrounding cold metal conducts heat away rapidly, thus acting as a powerful quench. The effect is shown clearly in fig. 100, Plate 22, representing a section cut through a single run deposit laid with a $\frac{5}{32}$ in. dia. electrode on the surface of a $\frac{1}{2}$ -in. plate of high-tensile steel. Such sections, polished and etched with a suitable reagent, are most informative when examined either visually or at a low magnification. The cast structure of the deposited weld metal provides a sharp contrast to that of the underlying parent metal, the normal structure of which has been affected by heat along the boundary. This thermally disturbed zone etches darkly and is quite distinct; its depth will obviously vary with the heat input.

So far so good, but the job is not complete without a hardness survey on the etched section. This is best carried out with a Diamond Pyramid Hardness Testing Machine, as described on p. 13, and the results so obtained have been inserted in fig. 100. The main point to remember is to take some of the hardness impressions on the parent plate as near as possible to the boundary, otherwise the peak of the hardness curve will be missed, for there is usually a very steep gradient in the first few millimetres. As we shall see later,

it is the hardness of this very narrow boundary layer that is the main criterion in assessing the weldability of high-tensile steels. For the low-alloy high-tensile structural steels of the $1\frac{1}{2}$ per cent manganese type (B.S.S. 548) welded with ordinary ferritic electrodes, it has been found that if the mean hardness of this boundary layer exceeds about H_D 350 there is a likelihood of cracking in joints which are restrained. In such cases the cracks are located in this hard layer which, on account of its brittle nature, cannot accommodate by plastic flow the very high thermal stresses set up during the welding operation.

The fact that this hard martensitic layer is caused by what amounts to a quenching operation suggests methods of control which may be applied in practice to minimise the effect by reducing the rate of cooling. It will be obvious that attempts in this direction are likely to succeed only with the lower alloy steels; they will have no effect on the higher alloy steels which harden even when cooled relatively slowly. Cooling rates can be reduced either by preheating the parent metal in the vicinity of the joint, or by increasing the heat input during welding. Increased heat inputs may be obtained by decreasing the speed of welding and/or by using larger gauge electrodes. Where possible, large gauge electrodes are to be recommended instead of small electrodes and slow welding.

The influence on weld hardening of electrode size, in relation to thickness of section, has been investigated by one of the authors by carrying out a series of single-run tests on plate specimens of a steel containing .26 per cent carbon and 1.6 per cent manganese. The tests were carried out on plates $\frac{1}{4}$ in., $\frac{1}{2}$ in., and 1 in. thick, using the same electrode in three different gauges, viz. $\frac{5}{32}$ in., $\frac{1}{4}$ in., and $\frac{5}{16}$ in. diameter. Comparable etched sections with mean hardness numbers (H_D) inserted are shown in fig. 100, Plate 22. It will be seen that for a given plate thickness there is a marked decrease in the mean hardness of the boundary zone as the electrode gauge increases. Again, for a given electrode gauge the hardness decreases as the plate thickness decreases. Note particularly in the case of the $\frac{1}{4}$ -in. plate that even with the smallest gauge electrode used the thermally disturbed zone extends right through the thickness of the plate. This means of course that the cooling effect of the surrounding metal is at a minimum in the thinnest plates, and it explains the reason for the relative

PLATE 29

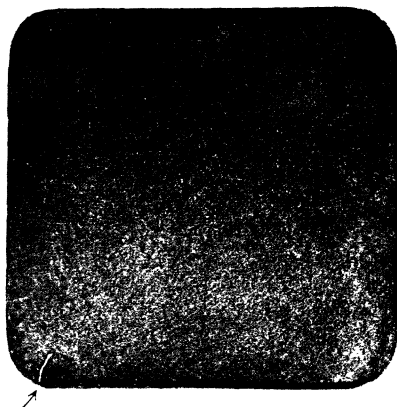


Fig. 111.—Roke in Steel Billet (Deep-etch Test)

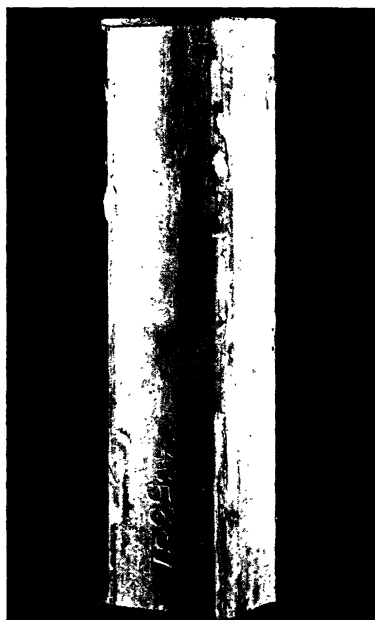


Fig. 112 —Shell in Steel Billets
(Deep-etch Test)

freedom from trouble in welding thinner as compared with thicker sections.

Weld Cracking Tests

To determine quantitatively the effect of this hardening on cracking, a number of tests have been devised which involve the deposition of weld metal under closely controlled conditions in either a fillet or a butt joint under severe restraint. One of the best known is the "Reeve Test". In this test

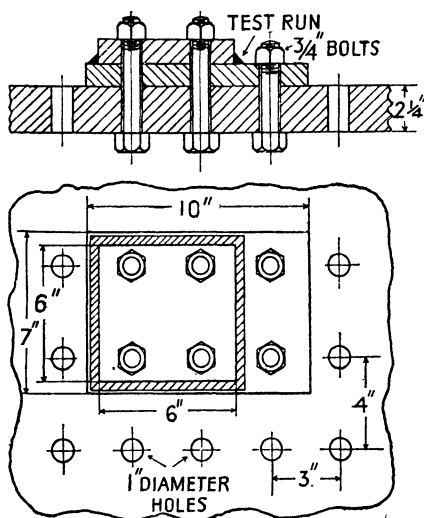


Fig. 101

(fig. 101) the plate specimen, of standard dimensions and usually about $\frac{1}{2}$ in. thick, is bolted securely to an underlying steel slab to prevent buckling. Three edges of the plate are fillet welded and the specimen is thereafter allowed to cool to room temperature. The fourth edge is then welded with the electrode and technique under investigation. This test weld, therefore, is deposited and cools down under the most extreme conditions of restraint, and any cracking tendencies are observed in the subsequent examination of sections cut

through the test run. Results obtained in comparable Reeve Tests on specimens of $\frac{1}{2}$ -in. plates to B.S. 548 and B.S. 968 are shown in fig. 102, Plate 23. The analyses of the plates used were as follows:

	C per cent.	Si per cent.	S per cent.	P per cent.	Mn per cent.
B.S. 548	·25	·06	·026	·016	1·58
B.S. 968	·22	·05	·027	·018	1·30

The test is completed by taking a Diamond Hardness Survey, and the hardness numbers obtained are shown in fig. 102. It will be observed in the case of B.S. 548 that the maximum hardness in the boundary zone is H_D 442, and that cracking has occurred in the vertical leg of the fillet, which is characteristic: moreover, the path of the crack is along the hardened zone. In the other specimen (B.S.S. 968), which shows no evidence of cracking, the maximum hardness of the boundary zone is only H_D 360.

Multi-run Deposits

The tests referred to above are concerned with the extremes of weld hardening, using single runs deposited from small-gauge electrodes without any preheat. It is interesting to observe what happens in the case of multi-runs. This is illustrated in fig. 103, representing a section cut from a butt joint on the same plate (B.S.S. 548) as was used for the Reeve Test, fig. 102, the electrode gauge being the same in both instances. Comparison of the two sections, figs. 102 and 103, demonstrates the influence of multi-runs in reducing the final hardness of the boundary zone, H_D 442 for the single run against H_D 220 for the multi-run weld. The explanation is quite simple. In the butt joint (the individual runs of which are apparent) the initial run at the bottom of the vee would cause approximately the same high hardness as in the case of the single-run fillet test. In this instance, however, there was no cracking because, in contradistinction to the Reeve Test, the plates in this test were not restrained. This initial hardening induced by the first run on cold plates is reduced, if not entirely eliminated, by the tempering effect of the subsequent runs, which incidentally are less prone in themselves to cause further hardening, because of the rise in the temperature of the plates.

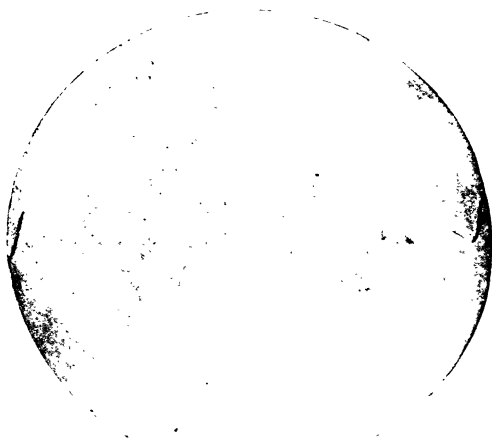


Fig. 113.—Overlap in Rolled Bar (Deep-etch Test)



Fig. 114.—Fish-tail (Sulphur Print)
(p. 146)

It should be quite clear that the foregoing remarks about the tempering or softening effect of multi-runs as compared with single runs apply only to steels of the type under discussion. In the case of the higher alloy steels the material is too sluggish in its response to tempering after quenching for this effect to have any appreciable influence. A weld in armour plate, for example, will harden to the same extent in the boundary zone irrespective of the number of runs, or indeed of the heat input as governed by the electrode gauge. Even preheating is insufficient in the normal type of armour to prevent cracking due to weld hardening. For this reason such steels are welded with special austenitic electrodes, the deposit from which appears to be peculiarly accommodating to the thermal stresses involved, thus diminishing the cracking tendencies.

Gas Cutting

Since weld hardening in high-tensile and alloy steels is precisely the same phenomenon as gives rise to hardening along the edges in gas cutting, it is appropriate to refer here to this process, which is so closely associated with welding in production. Cutting speeds, like welding speeds, determine the degree of hardening induced; the faster the cutting speed, the less of the surrounding metal is heated and therefore the greater its quenching effect. For this reason oxy-coal gas with its slower cutting speed gives a softer edge than oxy-acetylene. Edge hardening arising from gas cutting is also akin to weld hardening in its response to pre-heating.

The effect of hard edges on subsequent machining operations is obvious, but this can be rectified by grinding to a depth of at least $\frac{1}{16}$ in.; alternatively, an annealing treatment at $600^{\circ}/650^{\circ}$ C. for a short period will remedy matters. A much more serious consequence of edge hardening is cracking, and where this is likely to occur, as in thick sections, even after all due precautions such as preheating have been taken, then the material should be annealed at $600^{\circ}/650^{\circ}$ C. as soon as possible after cutting. In this connexion it should be noted that cracking often occurs some hours afterwards, the interval depending on the rate of cooling, which is slower the larger the mass. The absence of apparent cracking immediately after cutting sometimes creates a false confidence in the procedure, with unfortunate results. The guiding prin-

ciple when dealing with large masses of high-tensile or alloy steels should therefore be to anneal immediately after cutting. If no annealing furnaces are available, proceed very cautiously until the procedure adopted has been proved.

Finally, it is worth recording that high-tensile or alloy steels in the fully heat-treated condition, where they have a high Izod value or exhibit a fibrous fracture, are not nearly so prone to cracking in gas cutting as the same steels in the "as rolled" brittle condition, although the hardness induced is the same in both cases.

CHAPTER XIII

Defects in Steel and their Detection

Despite the large volume of research work which has been and is being undertaken, the manufacture of steel remains an art as well as a science. Consequently no steel is perfect, and the aim and object of producers and research workers alike is to make steel as good as it can be made. At the same time the economics of production may set a limit to quality standards, which must, therefore, depend upon the purpose for which the material is required.

To quote from a lecture on *The Non-Destructive Testing of Metallic Components*, by Bruce Chalmers,¹ "... while it might be criminal to permit a 1 per cent chance of failure of an aircraft component, and it might be merely bad policy to take a similar chance in the corresponding part of a car, it may well be cheaper and better to be prepared to give a free replacement in a vacuum cleaner."

Thus the ordinary tensile test, together with surface examination, may provide adequate quality control for mild steel plates for structural purposes. The manufacture of ball bearings for aircraft engines, on the other hand, demands the most rigid inspection standards at every stage in the long production chain. Thus there are available a very large number of tests designed to detect every possible defect that

¹ *Proceedings of the Physical Society*, Vol. LVI, p. 132 (1944).

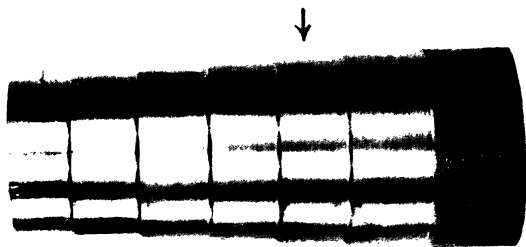


Fig. 115a.—Step Test $\times \frac{1}{4}$ actual size

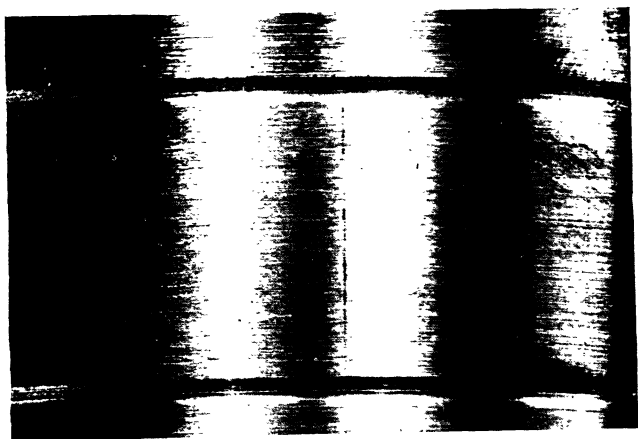


Fig. 115b.—Step Test. Actual size

can be present in steel. The particular test or tests to be applied on a given job and the interpretation of the results obtained demand a knowledge of steel-making processes and consideration of the purpose for which the steel is required. For example, slight axial segregation of impurities (sulphur, phosphorus, &c.) which would be of no consequence in a section of ordinary structural steel might, if present in a bloom, lead to central rupture during forging.

The tests described here are sufficient for detecting those defects which might be detrimental in further fabrication and in service.

The Deep-etch Test

In this test the general distribution of the constituents is revealed by the selective action of a suitable reagent on areas of different chemical composition. The reagent is a solution of an acid or a mixture of acids of varying strengths. Either hydrochloric acid or sulphuric acid is used. It is advisable to fix on a definite solution and to standardize this as well as the temperature and time of immersion, so that comparative results are obtained on different steels. For this purpose a solution of one part by volume of hydrochloric acid to one part volume of water is recommended. This solution has the advantage of remaining unchanged in concentration when heated. A porcelain dish or an enamelled cast-iron pan serves as a receptacle for the solution, which should be deep enough to cover the test specimens completely. This is heated on a hot plate or sand bath to a temperature of about 65° Centigrade.

The time required to obtain a suitable etch at this temperature depends upon the nature of the steel. For high carbon steels 30 minutes is sufficient, while 45 minutes are necessary for mild steel, and from one to three hours for alloy steels.

The preparation of the metal surface for the deep-etch test should also be standardized. It is not nearly so exacting as for micro-examination. A perfectly satisfactory surface can be obtained by grinding. The specimens, which usually include a complete section of the bars or billets, are cut off with parallel faces, one of which is ground to a smooth surface. Milling or turning may also be employed, but such methods are more costly. The specimen must be thoroughly cleaned and freed from all traces of oil or grease before immersion face

upwards in the etching solution. When etching is completed the specimen is withdrawn from the solution and washed in running water, a stiff scrubbing brush being used to remove the deposit which covers the surface. If it is desired to preserve the specimen for any time it should be washed in a weak hot solution of caustic soda to remove all traces of acid and then thoroughly dried. A thin film of oil applied with the fingers will prevent rusting.

The Sulphur Print Test

Sulphur printing has been very widely used in the examination of steels for segregation. The test is more difficult to carry out than the deep-etch test and has certain obvious limitations in the detection of defects in general. The test, however, is very useful, particularly when dealing with large forgings, &c., which cannot be conveniently deep-etched, and has the advantage that the sulphur print gives a record that can be filed.

It was shown in Table V, p. 42, that the elements which segregate to the greatest extent in the ingot are phosphorus and sulphur. These are the elements which constitute the harmful impurities in steel, therefore knowledge of their distribution is important. In a sulphur print this information is obtained in the form of an image of varying intensity on a piece of bromide paper which is treated with sulphuric acid and pressed into contact with the surface of the steel. When acted upon by the acid the sulphur and phosphorus in the steel form the gases sulphuretted hydrogen (H_2S) and phosphoretted hydrogen (PH_3) respectively. The evolution of the phosphide gas is very slight compared with the evolution of the sulphide gas, which is very rapid, consequently the print obtained is an image of the sulphur distribution mainly. This gas reacts with the silver bromide coating of the paper, forming a black silver sulphide image.

The preparation of the metal surface for this test requires considerable care. It must be perfectly smooth and free from tool marks. For the best results, a finish equivalent to No. 0 emery paper is recommended. When the surface is prepared it must be thoroughly cleaned and freed from all traces of oil or grease by washing with benzol or xylol. A soft bromide photographic paper (Kodak Libra Soft Double Weight) is cut to a convenient size and immersed for a few minutes in a

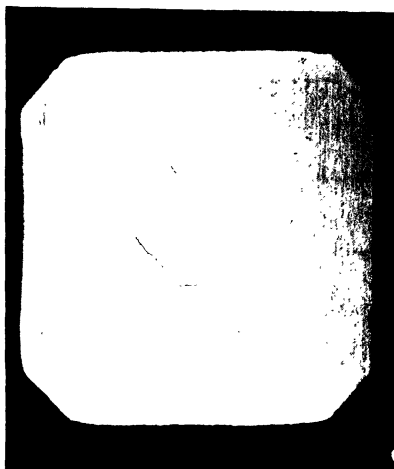


Fig. 116.—Hair-line Cracks (Crack Detection Test)



Fig. 117.—Effect of Shearing on Bend Test

2 per cent solution of sulphuric acid. The paper is then withdrawn and allowed to drip for about half a minute, after which it is very carefully laid on the metal surface. Contact between paper and metal must be uniformly established, and this requires somewhat delicate manipulation, especially if the surface is large. The formation of air or gas bubbles interrupts contact and so spoils the print.

A rubber squeegee as used for photographic purposes will be found useful in this operation, which must be performed without the slightest movement of the paper, otherwise the image will be badly smudged. The paper is allowed to remain on the specimen for 3 minutes, after which it is removed, washed for 30 seconds in running water, and fixed for 10 minutes in an alkaline solution of hypo. The fixing solution is made up as follows: $17\frac{1}{2}$ ozs. of sodium hyposulphite and 4 gm. of sodium bicarbonate are dissolved in water and the solution made up to $2\frac{1}{2}$ litres. The print is finally washed in running water for half an hour and is then dried.

If the sulphur print has been spoiled, it is essential, before taking a second print, that the surface be prepared afresh, using first 1M paper and finishing as before with No. 0.

Defects revealed by Deep-etch and Sulphur-print Tests

The more common types of defect revealed by these tests are :

1. Pipe or Axial Segregation.
2. Other types of Ingot Segregation.
3. Reeds.
4. Rokes.
5. Shell.
6. Overlaps.
7. Fishtail.

Pipe or Axial Segregation

This constitutes one of the commonest types of defects in steel. The term " pipe " is used loosely to cover all kinds of axial defects, but strictly speaking it should be confined only to those defects which arise from piping in the ingot, and as such it is invariably accompanied by segregation of impurities. A typical example of pipe is shown in fig. 104, Plate 25, which represents an etched specimen cut from a 3-in. square billet

of 3 per cent nickel steel. Before etching the specimen appeared to be quite sound, but the acid attack has clearly shown up the presence of pronounced axial segregates. For comparison a similarly etched specimen of another 3-in. square billet from the same cast of steel is illustrated in fig. 105. This specimen, it will be observed, is perfectly sound (Plate 25).

The presence of pipe, were it not detected in testing, would probably lead to considerable trouble during subsequent forging, as the steel would tend to rupture along the axis. While piped steel is the cause of many of the failures which occur during forging, the practical forger knows that it is quite possible by faulty manipulation to produce similar rupture at the centre of a billet of perfectly sound steel. The danger of pipe is further emphasized in wire-drawing, where the defective rods usually break up in cold drawing. In high-grade high carbon wire such as is used for winding ropes, slight traces of axial segregation will seriously affect the properties of the wire.

Fig. 106, Plate 26, shows a sulphur print of a section of a piped rail.

Other Types of Ingot Segregation

These include the so-called secondary segregates such as those derived from the "A" segregates of the ingot (see p. 43), as well as blowhole segregates, that is, blowholes which have become filled up with impurities of low melting-point during the solidification of the ingot. The latter are sometimes called "spot segregates", and are illustrated in fig. 107, Plate 27.

The segregation of "rimming steel" (fig. 108) was referred to in Chap. IV. Fig. 109 demonstrates the danger of using this type of steel for material where the cross-section is exposed, since the difference in composition between the centre and outside of the section results in differential chemical action, with the result that the segregated inner portion corrodes very rapidly (Plate 26). Some years ago rivets made of this type of steel resulted in very serious corrosion troubles in ships at sea.

Fig. 40, already discussed (Chap. IV), is a sulphur print showing the general distribution of sulphur in the ingot.

Reeds

Fig. 110 *a*, Plate 28, shows the rolled surfaces of a 2½-in. square billet of reedy steel which has been subjected to the

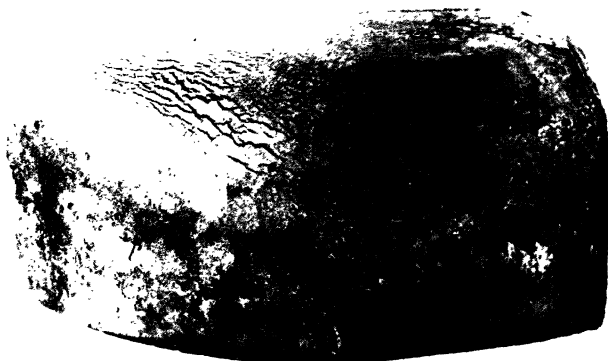


Fig. 118.—Burnt Steel



Fig. 119.—Burnt Steel. $\times 120$

deep-etch test. The acid has acted as a drastic pickling reagent removing the mill scale and exposing the underlying surface defects. The magnitude of these defects has of course been exaggerated by the attack of the acid, and due allowance must always be made for this in the deep-etch test. Fig. 110 *b* shows the cross-section of the same sample. This is the face of the specimen which has been prepared by grinding before etching, and it shows quite clearly how the surface reeds have originated from skin blowholes in the ingot. The cause of these blowholes may be over-oxidized steel as explained on p. 33, dirty moulds, incipient splash, or some other pouring defect. It is interesting to consider for a moment what happens to blowholes in ingots generally. If the blowholes are deep-seated and are not contaminated in any way by segregated matter they stand a good chance of being welded up during subsequent rolling. If, however, the blowholes are very near the surface of the ingot, the thin skin is likely to be broken, owing to its being scaled away during heating, thus exposing the blowholes to the oxidizing action of the flame. When withdrawn from the furnace the surface of the ingot is covered with little pits, the walls of which have been scaled by the furnace gases so that they are incapable of welding together in subsequent rolling. Each one of these pits is elongated into a reed which can be traced on the surface of the rolled material. Defects of this nature are very troublesome in small forgings where the machining allowance is small. This is especially the case where the skin is stretched at right angles to the direction of the reeds, for then they open up into splits which may extend into the material to a considerable depth. In finished material, such as plates, the presence of reeds results in a marked deterioration in the properties in the cross direction, i.e. at right angles to the length of the plate. In the tensile test, for example, the reeds act simply as so many minute notches cut across the test piece, causing it to break off short with very low elongation as if the steel were brittle.

Rokes

Unlike reeds, which are likely to affect the entire cast of steel, rokes are usually isolated defects which have originated in the ingot in the form of a crack or blowhole, or it may be a large non-metallic inclusion. A typical example of a roke is illustrated in fig. 111, Plate 29.

Shell

This is a surface defect caused by the presence of splash on the surface of the ingot. The occurrence of splash during the casting of metal into the ingot moulds has already been discussed on p. 36. The appearance of the defect on the surface of a billet is illustrated in fig. 112, Plate 29. As a rule the bottom portion of the ingot is more liable to splash because of the greater height of fall of the metal stream.

Overlaps

Improper roll design or faulty manipulation such as rolling at too low a temperature causes the metal to spread to such an extent that it is forced in between the collars of the rolls, thus forming a fin on each side of the bar. In subsequent passes these fins are lapped over, giving rise to the typical defect illustrated in fig. 113. The defect can nearly always be recognized by its occurrence simultaneously in diametrically opposite positions in the bar (Plate 30).

Fishtail

In the rolling of steel the surface of the bar or billet tends to elongate more than the interior, so that the back end has the appearance of a fishtail. When the mill is reversed and the bar is drawn through in the opposite direction partial welding of the fishtail may take place. These processes are repeated in the various passes, and if the discard from the ends of the finished rolled bar is insufficient the *local* defect which arises is known as "fishtail", an example of which is shown in fig. 114, Plate 30.

Step Tests and Inclusion Counts

These are employed to evaluate more or less quantitatively the non-metallic inclusion content of steel. The step test consists of turning a sample length of bar to various "stepped" diameters, as in fig. 115 (Plate 31). The surface finish must be smooth, so that small stringer inclusions if present may be distinguished by visual examination in a good light. The result of the test may be recorded as total length of inclusions per 100 square inches of surface area examined. This test is particularly useful as a check on the quality of shafting and machined bars for general engineering purposes.



Fig. 120.—Fatigue Fracture

Inclusion count methods employ chiefly the principle of comparing the result of micro-examination with standard graded micrographs, the grade numbers 1, 2, 3, &c., representing decreasing order of cleanliness. The representation of the complete ingot section is obtained by taking samples from the top, middle, and bottom; each sample is forged or rolled into a bar 1 to 1½ in. diameter, from which a short length is sectioned longitudinally through the axis of the bar. The specimen is fully quenched before being prepared in the usual way for micro-examination. Examination from edge to edge of the specimen, i.e. across the axis, gives a picture representing a complete cross-section through the axis of the ingot, and to minimize discrepancies it is usual to examine two or more such lengths. The magnification used and the number of fields of view examined are standardized. Each field examined is given a grade number in accordance with the corresponding field on the standard micrographs; the number of fields obtained in each grade is multiplied by the grade number and the total is added up, the resulting number being the inclusion number.

It is apparent from the foregoing that comparison between different casts of steel on the basis of inclusion numbers can only be made if the conditions are standardized throughout.

Crack Detection Tests

One of the most troublesome defects to which steel is prone is known as "hair-line cracks". They are liable to occur in steels which cool from the rolling temperature at such a rate as results in partial or complete hardening, and, as might be expected, are more common in the higher alloyed steels. Basic steels, particularly when made by the electric process, are more prone to this defect than are acid steels, and hydrogen is generally considered to be the cause; the actual mechanism is still not quite understood. Hair-line cracks can be prevented by suitable treatment of the ingot or by controlled cooling of the rolled or forged material. Once this has been done satisfactorily the steel is rendered immune and further heating and cooling will not produce them.

The cracks are so fine that they cannot be seen on a polished section. If, however, the section is placed in a strong magnetic field and is treated with a fine suspension of mag-

netic oxide of iron (Fe_3O_4) in oil, the polarity set up in any discontinuity causes the fine magnetic particles to be directed to that portion of the section, and in this way the hair-line cracks are revealed (fig. 116, Plate 32). It will be noted that the cracks are deep-seated, and this is characteristic of this type of defect.

Hair-line cracks will weld completely on further hot work, but too rapid cooling thereafter may result in the production of fresh cracks. The smaller the section of the finished bar or forging the less will be the tendency for these cracks to occur.

Other Causes of Failure

The foregoing tests, together with surface examination, chemical analyses, and such mechanical tests as may be required, are designed to ensure that the manufacturer supplies satisfactory and reliable steel. Failures, however, may arise from causes other than material defects, and may be due to

1. Improper workmanship,
2. Bad design, or
3. Unsatisfactory service conditions.

1. A very common cause of failure of plates in fabrication arises from the attempt to bend them with rough-sheared or gas-cut edges, with sharp corners or under conditions of severe restraint. To illustrate one example, fig. 117 shows the difference between bending with sharp corners (A) and with rounded corners (B), Plate 32.

Bending steel in the region of 300°C. is liable to cause fracture, since this is the blue-brittle range of temperature. Figs. 118, 119 (Plate 33), illustrate a common type of failure frequently attributed to poor steel quality, but which is actually due to burning resulting from intense local overheating. Burning consists of incipient fusion at the grain boundaries, and hence the micro-structure shows a typical inter-crystalline failure (see also p. 50).

2. The importance of design in relation to fatigue has already been discussed (Chap. I). Fig. 120, Plate 34, illustrates a typical example of fatigue failure arising from too sharp a radius at a change of section.

A

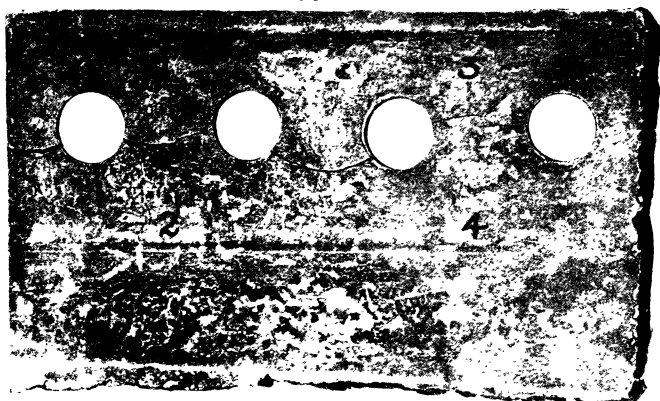


Fig. 121.—Section of Cracked Wrapper Plate. $\times \frac{1}{4}$

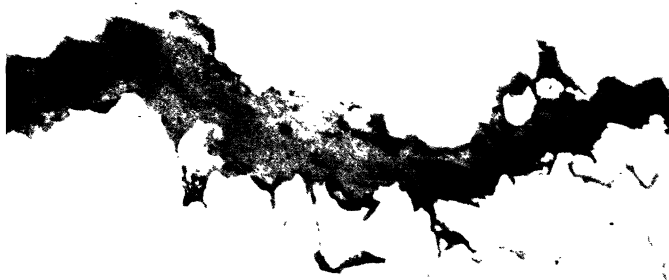


Fig. 122.—Inter-crystalline Crack in Wrapper Plate. $\times 250$

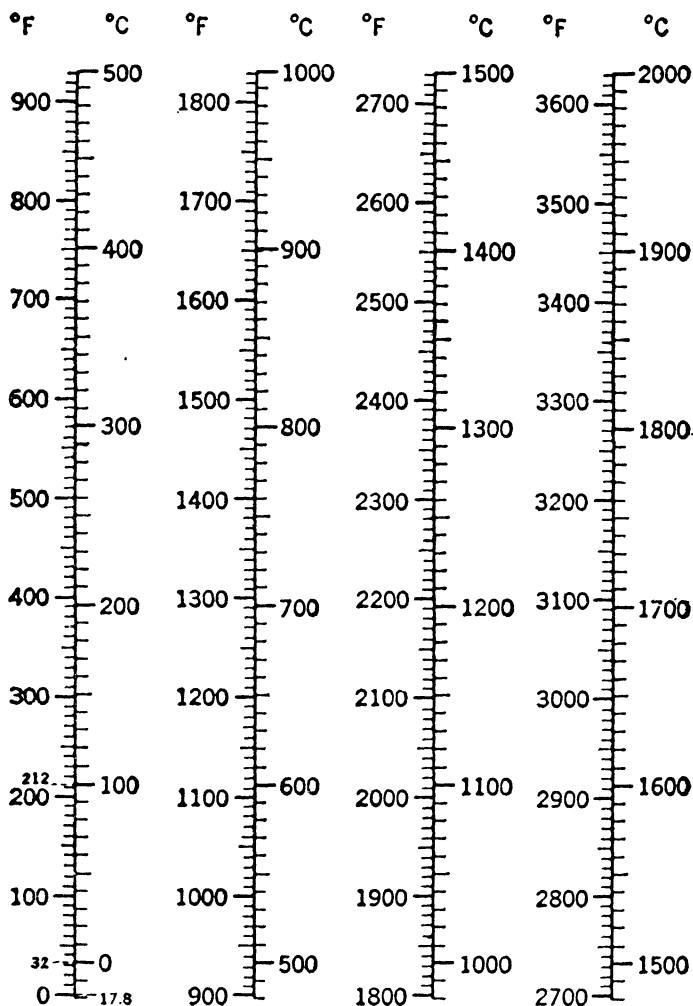
3. Corrosion troubles almost invariably arise from service conditions and not from defects in the steel. Oil in feed water is a very common cause of pitting, a most dangerous form of corrosion. Chemical attack on material in a state of stress produces a form of corrosion which is typically inter-crystalline in character. An example of this is the cracking caused by the action of alkaline feed water on boiler plates under stress. The high concentration of the caustic solution necessary to initiate chemical attack is reached in the seams between plates, where the feed water penetrates, and from which only steam escapes. An example of a crack so induced in a boiler plate is shown in figs. 121 and 122 (Plate 35). Caustic cracking may be prevented by suitable treatment of the boiler feed water.

Failure may arise in shafting through seizing as a result of inadequate lubrication, causing overheating and tearing of the metal.

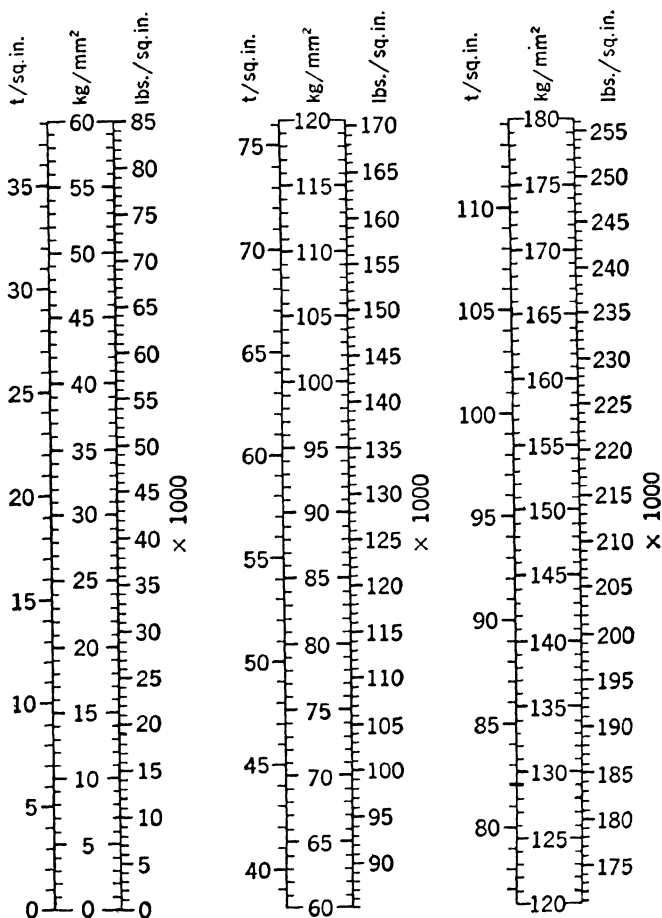
The foregoing examples indicate only some of the defects and failures which may arise in perfectly satisfactory steel after delivery, but are sufficient to indicate that the customer is not always right.

TEMPERATURE CONVERSION SCALE

Fahrenheit — Centigrade



STRESS CONVERSION TABLE Tons/sq. in. — Kg./mm.² — lbs./sq. in.



SELECTED BIBLIOGRAPHY

GENERAL

Journal of the Iron & Steel Institute, 4 Grosvenor Gardens, London, S.W.1.

MECHANICAL TESTING

Batson & Hyde: *Mechanical Testing*. London: Chapman & Hall, Ltd.

MICROSCOPY

Greaves & Wrighton: *Practical Microscopical Metallography*. London: Chapman & Hall, Ltd.

STEEL MANUFACTURE

Harbord & Hall: *Metallurgy of Steel*. London: Chas. Griffin & Co.

HEAT TREATMENT

Bullens: *Steel and Its Heat Treatment*. London: Chapman & Hall, Ltd.

Hardenability of Alloy Steels—Symposium (1939), American Society for Metals, Cleveland.

CARBON AND ALLOY STEELS

Wrought Steels (B.S. 971). The British Standards Institution, 28 Victoria St., London, S.W.1.

COLD WORKING

Adam: *Wire Drawing and the Cold Working of Steel*. London: H. F. & G. Witherby.

Jevons: *The Metallurgy of Deep Drawing and Pressing*. London: Chapman & Hall, Ltd.

CORROSION

Hudson: *Corrosion of Iron and Steel*. London: Chapman & Hall Ltd.

CREEP

Tapsell: *Creep of Metals*. London: Oxford University Press.

WELDING

Harris: *Metallic Arc Welding*. London: Edward Arnold & Co.
Arc Welding of High Tensile (Low Alloy) Structural Steels. Inst. of Welding, 2 Buckingham Palace Gardens, London, S.W.1.

PHYSICAL TESTING

Chalmers & Quarrel: *The Physical Examination of Metals*: Vol. I—Optical Methods, Vol. II—Electrical Methods. London: Edward Arnold & Co.

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